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THE LUNAR ORIGIN OF TEKTITES

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SUMMARY

Recent research results from the discipline of atmosphere entry aerodynamics have been applied to the study of tektites, especially those found in Australia. Hypervelocity ablation experiments with tektite glass have reproduced in the laboratory the same surface sculpture patterns, the same geometric relationships, the same systematic alteration in internal striae, and the same types of coiled circumferential flanges as those found on the Australian tektites. The over-all evidence establishes that the australites are objects which have entered the earth's atmosphere as individual pieces of rigid glass and have been shaped by severe aerodynamic heating.

Experiments have been conducted on molten glass ejected into the atmosphere with various viscosities and velocities. The results demonstrate that the configurations commonly formed by the action of aerodynamic pressures on fluid glass do not resemble the australite primary shapes. These experiments also show that the dominantly spheroidal forms of the primary australites were formed in an environment where the atmospheric density was many orders of magnitude less than that at the earth's surface. These results contradict the hypotheses that the australites originated from either the earth, or the other atmosphere-shrouded planets.

Various comparisons are made of experimental and calculated characteristics of tektite ablation. Calculations of the surface temperature during ablation, the recession rate, the mass loss due to vaporization, and the distortions of internal glass striae are shown to be in close accord with measurements. The experimentally confirmed methods of calculation, when applied to the various observed characteristics of the australites - namely, their amount of ablation, their ring-wave sculpture patterns, and their distorted internal striae - enable the atmosphere-entry trajectories to be determined within certain limits. These trajectories are imcompatible with an origin from outside the solar system, and, in agreement with the conclusions drawn from studies of their primary shapes, are incompatible also with origin from the earth and the other planets; the moon is the only known celestial object of origin which is compatible with the australite entry trajectories determined herein.

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A comparison is made of the distribution of chemical elements in tektites, earth crust, meteorites, and other cosmic bodies; and a brief discussion is presented of the chemically differentiated nature of the lunar crust to which the over-all evidence points.

INTRODUCTION

The scientific literature on tektites now spans a history of over 170 years and exhibits a wonderful proliferation of diverse hypotheses as to the origin of these remarkable glass objects. In certain respects the history of thought on tektites has paralleled that on meteorites. During the nineteenth century - the first century of scientific inquiry on meteorite origin - a plethora of hypotheses were advanced as to the origin of the stones and irons which fell from the sky: they were suggested as coming from earth volcanoes, from moon volcanoes, from the sun, from lightning fusing atmospheric dust, from comets, from the region where the asteroids now are, from the fixed stars, and from Jupiter and the other planets. During a comparable period of inquiry on tektite origin - from the first report of australite discovery by the eminent naturalist, Charles Darwin (1844), to the penetrating paper on tektite origin by the American scientist, H. H. Nininger (1943) - all of these hypotheses independently have been offered in an effort to explain the puzzling knowledge about tektites. In addition, tektites also have been suggested as originating from the splash of a cosmic body impacting the earth, from drippings left behind when the moon was torn from the earth, from meteoritic impact on the moon, from ball lightning striking terrestrial sediments, from prehistoric civilizations remarkably advanced in glass technology, and from ablation drops shed behind a parent cosmic body passing through the earth's atmosphere.

The extended histories of meteorite and tektite investigations alike provide instructive examples of how puzzles in natural science, which center on mysterious objects of unknown origin, often are solved: a deluge of hypotheses is advanced as the inevitable companion of inconclusive initial data; the process of solution slowly advances through the time honored method of trial and error, wherein each hypothesis is compared with accumulated observational data and rejected if incompatible; progress is made incrementally by rejecting bad hypotheses as well as by accepting good ones; and some of the key steps, which for decades remain inaccessible to the particular scientific disciplines initially concerned with the objects, often become suddenly comprehensible through "by-product" results from a new, or different, scientific discipline. It is the design of the present paper to survey some relatively new research results obtained from the young discipline of atmosphere entry aerodynamics as applied to the old problem of tektite origin.

The present work may be fairly termed an example of scientific by-product. Both the experimental facilities and the theoretical techniques upon which this work is based were developed from researches of scientists who were unconcerned with, and generally unaware of, objects called tektites, but were involved with the problem of protecting spacecraft and missiles from severe atmospheric entry heating. An initial application of these aerodynamic-entry researches to the field of tektite study (Chapman, 1960) has indicated the singularly important evidence which aerodynamics brings to bear on the problem of tektite origin. In this study it was concluded: (1) that the Australian tektites exhibit unmistakable evidence of having been shaped by aerodynamic ablation of rigid glass objects during hypervelocity entry into the earth's atmosphere, and (2) that this aerodynamic evidence is sufficiently complete to deduce both the initial velocity and the initial angle of entry into the earth's atmosphere. The unique importance of this type of knowledge lies in the simple fact that the entry velocity and the entry angle determine the earth approach trajectory, and the trajectory determines the place of tektite origin. In a recent paper (Chapman, Larson, and Anderson, 1962) we have elaborated on experiments which document conclusion (1); in this paper we elaborate similarly on conclusion (2). For completeness, the evidence pertaining to conclusion (1) also is reviewed briefly herein and brought up to date.

A magnificently complete aerodynamic record has been imprinted on the thousands of tektites found strewn over the southern portion of the Australian continent. At present a substantial portion, though not all, of this record can be read with quantitative clarity. It is known that the amount of ablation by aerodynamic heating can be determined from studies of external shape; that the heating rates prior to termination of ablation can be ascertained from certain distortions of the internal striae pattern; and that the stagnation point pressure prior to termination of ablation (as shown in this report) can be deduced from certain sculpture features on the tektite's front face. Calculations of the amount of ablation and the distortion of striae previously have been used to determine the approximate entry trajectories of several australites (Chapman, 1960), and these trajectories pointed to the moon as the source of australite origin. In this paper the sculpture pattern, as represented by the spacing between ring-wave flow ridges, is similarly used for independent trajectory determinations.

In the preparation of this report an underlying tenet has guided the choice of material and the manner of presentation, namely, that the majority of scientists interested in tektites are from diverse disciplines other than atmosphere entry aerodynamics. It is recognized that scientists from long-established disciplines rightfully are wary of results from a new discipline; and that few of the many geologists, geochemists, mineralogists, naturalists, and petrologists, who have conducted the principal body of previous research on tektites, are familiar with the substance of the framework underlying the atmosphere-entry evidence as to tektite origin. Many scientists from these diverse fields have favored a terrestrial origin for tektites. When a research topic intertwines so many disciplines, and controverts the published views of so many scientists, any new result that may be demonstrable or accepted by individuals in one discipline often is disregarded or rejected by others in a different discipline, especially if the results appear to be only "calculated" ones. Consequently, in recognition of these circumstances, and of the singular importance of the aerodynamic evidence on tektite origin, we have sought throughout to conduct measurements wherever explicit data are missing, to utilize thorough analytical methods whenever computations are made, and to document in detail the combined experimental-analytical foundation upon which the final conclusions are based. In this way we hope that a clearer view may be revealed of the strength behind the aerodynamic evidence as to the origin of the Australian tektites.

In carrying out our program, we have had the indispensible assistance of many individuals. Our indebtedness is especially great to Dr. George Baker of the University of Melbourne, who, during the past three years, has generously provided us with extensive unpublished data on his near perfect Port Campbell australites, as well as with various other observations that have advanced the progress of this research. Our acknowledgement also is extended here to Professor G. H. R. von Koenigswald, of the University of Utrecht, who provided several Java tektites for detailed study. To our colleagues at the Ames Research Center, Mr. Lewis A. Anderson and Mr. Norman B. Zimmerman, who have assisted with the tektite ablation experiments, Mr. Frank J. Centolanzi, who has measured the vapor pressure of tektite glass, Mr. George Lee, who has conducted experiments on the breakup of molten glass and the ablation of glycerin glass, and to Mr. Fred Matting, who has assisted with some of the ablation calculations, we gratefully express our indebtedness and our appreciation.

EVIDENCE FOR ATMOSPHERE ENTRY OF AUSTRALITES

A detailed record of hypervelocity ablation by aerodynamic heating has been imprinted on the exterior surface, and implanted within the interior structure, of the better preserved Australian tektites. In an earlier paper (Chapman, Larson, and Anderson, 1962) we have described some aerodynamic experiments with tektite glass wherein a number of the curious and singular features observed on tektites were clearly reproduced by ablation in a hypervelocity air stream. More recently we have observed some additional features of congruency between natural tektites and ablation products from the aerodynamic laboratory. It is the design of the present section to review briefly the previous evidence, and more completely the recent supplementary evidence, which demonstrates that the australites were sculptured by aerodynamic ablation during entry into the earth's atmosphere. This evidence is drawn from independent observations on external sculpture, geometric relationships, internal structure, and aerodynamic stability of tektite forms.

The most unique feature of tektite sculpture is the presence of ring-wave flow ridges and circumferential flanges on "button" type tektites found thinly spread over the southern half of the Australian continent. Sometimes the flow ridges form a spiral ring and sometimes a series of concentric rings. Aerodynamic ablation experiments have reproduced quite closely the same systems of ring-wave flow ridges and the same types of circumferential flanges. In figure 1 a summary comparison is presented of three different tektite glass models ablated in an arc jet, with three different Australian tektites now housed in the British Museum. Artificial products are at the top, and natural tektites at the bottom. All are shown enlarged to a common size. Their actual diameters very somewhat, being 21, 16, and 22 mm, respectively, for the artificial tektites shown from left to right in front, side, and base view; and 25, 24, and 23 mm, respectively, for the corresponding natural tektites. The principal features of congruity in sculpture between australite buttons and aerodynamic artifacts are self-evident from this figure, and require no further comment.

Some of the very rare australite shapes, as well as the more common button types described above, can also be reproduced in the aerodynamic laboratory. A photograph of the side view of an uncommon tektite configuration is presented in the lower portion of figure 2. This reproduction is taken from plate VIII of Baker's treatise (Baker, 1959) wherein the location of find is listed as being near Gladstone, Northeast Tasmania. In contrast to the more typical australite buttons, this tektite possesses a remarkably wide flange shaped like a hat brim, brings about a significant reduction in the laminar convection heating rate which varies as $R_F^{-1/2}$, and this aspect of tektite ablation physics must be considered in an accurate calculation of the amount of ablation. After the stagnation point recesses to beyond about $y_s = 0.6\ R_B$, the value of R_F begins to decrease, as illustrated in figure 3 by the curve that extends to the point $y_s = 1.45\ R_B$, $R_F/R_B \approx 0.8$. The termination of this curve corresponds to the point at which the arc was extinguished and ablation ceased. If ablation had been terminated at some earlier time, a point anywhere along this curve could have been obtained for the final value of R_F/R_B. Thus the various curves representing aerodynamic ablation are to be compared with the various data points in figure 3 representing terminal R_F/R_B values for Australian tektites. These data points correspond to R_B values greater than 0.7 cm (most are in the range $0.8 < R_B < 1.2$ cm) for which surface tension of the flange melt does not affect significantly the over-all geometry. For values of R_B below about 0.7 or 0.6 cm, surface tension phenomenon becomes important; and the R_F/R_B values, from both the aerodynamic experiments and the tektite measurements, can be considerably higher and the self-protective mechanism more important. It is noted that australites from different tektite collections are included in figure 3; the circles represent perfect buttons, and the circles with horizontal lines represent lenses and incomplete buttons, from the collection of Dr. George Baker, to whom we are indebted for sending these data in advance of their publication (Baker, 1962a); the squares represent australites from the collection of the Smithsonian Institute of the U. S. National Museum kindly loaned to us by Mr. Edward Henderson; the diamonds represent two buttons from the collection of Dr. William Cassidy; and the triangle symbol represents the remarkable hollow button tektite of Steltzner (1893). The essential point illustrated by this figure is that the geometric relationship between surface curvature and dimensions of Australian tektites is in quantitative harmony with the geometric relationships produced by aerodynamic ablation.

In addition to the congruity in geometry between Australian tektites and aerodynamically ablated tektite glass, there also exists a conformity in internal structure. It has long been known that the australites were twice melted (Fenner, 1934; Barnes, 1939; Baker, 1944, 1959), first, when some parent tektite material was fused to form primary glass bodies (mostly spheres) and, second, when these bodies were subsequently heated to form the flow ridges and flanges. The first heating left an irregular, often contorted, striae pattern that constitutes a distinguishing characteristic of tektite glass (Barnes, 1939, 1960). The second heating left (1) the chemical composition of the flange, relative to the core, selectively deficient in the more volatile oxides (Taylor, 1961), (2) the striae pattern within the flange coiled always in a consistent direction (Baker, 1944), and (3) the striae pattern within a very thin frontal layer systematically distorted in a particular mathematical fashion (Chapman, 1960). It is to be noted that these three conditions, produced during the second heating of the australite, are concordant with those produced at hypervelocities by the heating of aerodynamic friction. The observed selective loss of the more volatile alkali elements during flange formation, as estimated by Taylor (1961) from comparative losses observed with powdered tektites in a d.c. arc, corresponds to a temperature of a few thousand degrees Kelvin; ablation temperatures for tektite glass during atmosphere entry readily reach into this range (typically, 2500° to 2900° K) where substantial vaporization of the melt flow occurs. That the type of stria coiling observed within australite flanges also is produced by aerodynamic ablation may be seen from the photographs in figure 4 of two thin sections; that on the right is reproduced from and only a single ring-wave flow ridge. Shown for purposes of comparison in the top portion of figure 2 is a configuration of glycerin glass photographed during an aerodynamic experiment. Here the wind-tunnel stream was directed vertically upward (a portion of the cylindrical support to which the model is attached can be seen at the top of the photograph). This configuration, produced by aerodynamic ablation, exhibits a hat-brim flange, and a single ring-wave flow ridge, strikingly similar to those on the Tasmanian tektite. It is significant that such an uncommon tektite configuration could be obtained in our experiments only by adjusting very carefully the test conditions so that the aerodynamic force tending to push the ablated melt flow upward just balanced the gravitational force tending to pull it downward. A small perturbation in stream conditions from those of this delicate adjustment was found to result either in a downstream movement and a contraction of the flange, coupled with the appearance of more than one ring wave, or else in a detachment of some portion of the flange brim coupled with a reshaping of the remaining flange portion. In this experiment the gravitational body force in the vertical wind tunnel provides a dynamically similar analogue to the deceleration body force in an entry flight; both forces are directed parallel to the axis of symmetry and are exerted uniformly over each volume element; and the fact that the gravitational force in the wind tunnel is smaller than the corresponding decelerational force in flight is precisely compensated by proportionally smaller aerodynamic forces, so that mechanical similarity is achieved between laboratory and flight conditions. Among the many thousands of australites, the relatively rare observance of this shape, with its wide, hat-brim flange, is a circumstance entirely consonant with, and clearly explained by, the experimental observation that delicately adjusted aerodynamic conditions are required to produce such a configuration. We see, therefore, both congruence between tektite configuration and aerodynamic sculpture, and consonance between observed rarity of this configuration in the strewnfields and required selectivity of the dynamic conditions for its production.

Additional corroborating evidence that the present sculpturing on the better preserved Australian tektites is aerodynamic in origin has been obtained from a study of the geometric relationship between surface curvature and tektite dimensions. The geometric quantities entering this relationship are the front surface radius of curvature R_F, the back surface radius of curvature R_B, and the depth D_e measured along the axis of symmetry. When a tektite glass sphere, of radius R_B, is exposed to severe aerodynamic heating, the radius of curvature of the receding front face varies with the depth of ablation $y_s = 2R_B - D_e$ (a sketch illustrating y_s, R_B, and R_F is included as part of figure 3). Photographs of the tektite ablation process in a hypervelocity arc jet show, as would be expected, that melting begins at the stagnation point where the heating is most severe; the fluid glass in the stagnation region is moved by aerodynamic forces radially outward to the cooler equatorial region where it accumulates in a toroidal-like bulge on top of the original spherical surface. As the bulge accumulates, R_F increases from its original value of R_B. This trend is evident in figure 3 from the solid curves representing the variation in R_F/R_B with y_s/R_B. Each curve was obtained from cinematographic film records of the ablation process; the different curves correspond to different tektite glass compositions (e.g., 65-percent silica for the lower curve, 72 percent for the upper) and to different aerodynamic heating conditions. The value of R_B for these experiments, 0.79 cm, is comparable to the value of 0.85 cm listed by Baker (1955) as the average for australite buttons. In a certain sense the initial response of R_F to the ablation process may be viewed as a self-protective one; the increase in R_F to values the order of 1.5 R_B

plate X of Baker's treatise (1959), and represents a meridional thin section cut from australite No. 279 of his collection; that on the left represents a meridional thin section cut from one of our models of aerodynamically ablated tektite glass. In this latter case the pre-ablation model was constructed from a rizalite specimen (7 gm, Pugad Babuy, Luzon). In both thin sections a common manner and direction of flange coiling is evident.

Correspondence of certain fine details of flange striae patterns also has been found between natural tektites and ablation products from the aerodynamic laboratory, as may be seen from the comparison in figure 5. The flange formed by aerodynamic ablation and that formed by the second heating of the australite alike show curious, zigzag striae in the outer entwinings of the flange.

Of greater significance, perhaps, than these immediately perceptible similarities is the less evident correspondence in striae patterns near the front face of natural tektites and aerodynamic artifacts. This correspondence is revealed by the particular mathematical fashion in which the striae have been distorted within only a very thin layer just beneath the front surface. In figure 6 are presented thin section photographs from one of our models (IC 202-2) in which the thinness of the melt layer may be seen. This model was constructed from the tail portion of an indochinite teardrop (18 gm specimen, Dalat, South Viet-Nam) wherein the basic striae prior to ablation tended to follow a common direction roughly parallel to the axis of symmetry. This enables a clear separation to be made of the basic and distorted striae patterns. Various quantities entering the analysis of striae displacement are also illustrated in this figure. The mathematical characteristics of striae displacement (d) varying linearly with distance (x) from the stagnation point, and exponentially with depth (y) below the surface, are the characteristics required by aerodynamic ablation theory. These particular characteristics are exhibited both in australites and in models of tektite glass ablated by aerodynamic heating, as shown in an earlier paper (Chapman, Larson, and Anderson, 1962). Some data taken from this paper are presented in figure 7 which illustrates the exponential-like variation of stria displacement $d(y)$. The curve labeled "australite B 279" represents registration No. 279 of Baker's collection, and that labeled "aerodynamic ablation" represents a model (A-123) from our laboratory experiments which, prior to ablation, was ground from a piece of Australian tektite glass (7 gm, core, Nullarbor Plain). It is evident that both the natural tektite and ablated model exhibit the exponential-type variation required by aerodynamic ablation theory; but the two curves are shifted in depth by an amount $\Delta y = 0.013$ cm. This shift is attributed to erosion by the agents of chemical etching and mechanical abrasion that have acted on the australite's front face during its many millenia of terrestrial exposure. Thus the present front surface would have been about 0.013 cm below the original, freshly ablated surface, and an allowance for this will place the two $d(y)$ curves in excellent agreement.

One of the most characteristic features of hypervelocity aerodynamic ablation is that the melt layer invariably is thin; the exponential decrement for the examples in figure 7 is only 0.1 mm, and the entire melt layer is only a few tenths of a millimeter thick. Such thinness is a manifestation of the extremely high heating rates which produced the systematic striae distortions, and at the same time, is a firm indication that the glass body so heated was structurally rigid prior to ablation. Stone meteorites are exposed to the same physical phenomena, and invariably exhibit, for similar reasons, a fusion crust of comparable thinness.

As illustrated in figure 8, the correspondence in systematic striae distortions between natural tektites and ablation products extends also to the variation with distance x from the stagnation point ($x = s + d$); both exhibit the linear $d(x)$ variation required by aerodynamic ablation theory. The somewhat different inclination of the two straight line approximations for $d(x)$ is not significant, inasmuch as the slope depends on the particular heating rate, radius of curvature, and fixed depth y selected for the measurements.

As a final source of evidence that the australites have entered the earth's atmosphere, attention is called to their aerodynamic stability and to the compatibility of the orientation for such stability with that indicated by surface melt patterns. Technical details relating to a study of the static and dynamic stability of australite configurations have been given in an earlier paper (Chapman, Larson, and Anderson, 1962) and will not be repeated here. Mention is made, however, of the end result. From an analysis of the statistics given by Baker (1956) as to the shape categories into which about 8,000 australites can be classified, it has been found that over 98 percent represent configurations possessing both static and dynamic stability during a descending entry into the earth's atmosphere. Their sculpture decisively indicates a stable flight; moreover, the particular orientation for aerodynamic stability is precisely compatible with the particular orientation indicated by the melt pattern observed on each configurational category. Such a high percentage of aerodynamically stable flights would not occur in ascending trajectories (as these encompass unstable flight conditions), nor among objects, such as meteorites and other tektite groups, of less regular shape than the figures of revolution of the primary australites.

Summarizing thus far, we have seen that the external sculpture, the internal structure, the geometric relationships, and the aerodynamic stability of the Australian tektites leave no doubt that they were shaped by severe aerodynamic heating sometime in the distant past when myriads of glass spheroids descended at hypervelocity into the earth's atmosphere. Ablation has modified markedly the primary shapes possessed by these tektites before their atmospheric plunge; and the extent of this modification, as determined by the difference between the original primary shape and the aerodynamic secondary shape, is one important key to their origin. In the section which follows, previous evidence is reviewed and some new aerodynamic experiments are discussed which pertain to the formation of primary tektite shapes.

AERODYNAMIC EVIDENCE PERTAINING TO THE ORIGIN OF PRIMARY AUSTRALITE SHAPES

The idea often has been advanced that the australites were formed by aerodynamic pressures during the passage through the air of soft, molten glass (e.g., Darwin, 1844, Walcott, 1898, Grant, 1909, Moore, 1916, Hardcastle, 1926, Lacroix, 1932, Spencer, 1933a, and Fenner, 1938). We have demonstrated earlier, however, that the secondary shapes of the australites were formed by the action of aerodynamic heating on rigid glass, rather than by aerodynamic pressures on soft glass; but we have not previously ascertained whether the primary shapes could have been formed by aerodynamic pressures.

From studies of thousands of australites, it has been concluded that about 80 percent of the primary shapes were either spheres, or oblate spheroids close to spheres (Fenner, 1938; Baker, 1955, 1956). An example of a meridional section from a cast of a tektite, for which it is certain that the original shape was very close to spherical, is illustrated in figure 9. This australite, kindly loaned to us by Dr. William Cassidy, is identified in his collection as No. 625, from Charlotte Waters. Curvature gauges applied to different areas of the spherical base revealed the variation in curvature, from that of a sphere of 1.83 cm diameter, to be only about 1 or 2 percent. As is indicated in this figure, the volume of flange plus core accounts for all but a small portion of the volume of the primary sphere; the remaining portion amounts to 11 percent of the primary-sphere volume. This latter amount is comparable with the calculated amount of glass vaporized in the process of forming the flange melt. There could not have been more material lost from the front portion of the primary object than that accounted for since, if there were, the primary configuration would have been a prolate spheroid, a shape which is aerodynamically unstable with its longer axis parallel to the flight direction and which would have flown in an attitude orientated 90° from that observed. Thus, on australite buttons of this type, the original primary shape is known to have been very close to a sphere, a natural shape produced by the forces of surface tension when other distorting forces are negligible.

A series of experiments on the formation of primary shapes from the breakup of fluid glass - in both the presence and the absence of aerodynamic forces - has been conducted as part of our tektite research program. These experiments were conducted by our colleague, Mr. George Lee. Lead glasses at various temperatures were investigated in order to cover a wide range of viscosity (0.2 to 280 poise). Three different methods were employed for ejection of the molten glass: (1) low velocity ejection nearly vertically upward into the atmosphere from a height of 34 m above the ground, in order to produce primary shapes by breakup under conditions where aerodynamic forces are small compared to surface tension forces; (2) high-velocity ejection nearly vertically downward from the same height, in order to produce primary shapes by breakup from aerodynamic forces; and (3) ejection in a large vacuum chamber in order to produce primary shapes in a near vacuum. In each case a multitude of forms were recovered on the surface, the smaller of which were clearly solidified before impact. Large drops, of course, did not have sufficient time to solidify before landing, and their splattered forms are not included in the study.

One significant result from these experiments is that the primary shapes varied markedly with the viscosity of the glass. In a low-velocity ejection, wherein the aerodynamic forces are small compared to surface tension forces, it has been found that glass of a certain viscosity will break up, through the action of its own internal motions and the forces of surface tension, into shapes which are similar in form and in relative number to the primary shapes of the australites. Figure 10 illustrates the relative proportions of various configurations found when the glass viscosity was 2.9 poise and when the aerodynamic forces were small compared to surface tension forces (low-velocity ejection). Each category shown represents approximately one-fourth of the total number recovered of its group. It is evident that round forms are most abundant, then elongates (ovals, boats, dumbbells, canoes), teardrops, and nondescript forms. This distribution of primary shapes for $\mu = 2.9$ poise is similar to that of the australites, but the distribution obtained with either larger or smaller viscosities is dissimilar, as the following table illustrates:

	Viscosity poise	Percentage of various shapes			
		Round forms	Elongates	Tear-drops	Nondescript
Present experiments	0.8	95	4	1	0
	2.9	76	11	7	6
	35	8	19	62	11
	135	0	5	35	60
Australites		73	23	3	1

The figures given for the australites are based on a total of about 8000 tektites from the combined Victorian, Nullarbor Plain, and Charlotte Waters areas (Baker, 1956). Included within the round form category are buttons, lenses, cores, and discs; in the elongate category are ovals, boats, dumbbells, and canoes. Relative to the australite-like distribution obtained for $\mu = 2.9$, the percentage of shapes in each category changed completely as the glass viscosity was changed: when it was reduced by a factor of about 4, to 0.8 poise, almost all the forms were spherical; when increased by a factor of about 12, to 35 poise, the majority were teardrops and few were round forms. Whereas, at a still higher viscosity, of 135 poise, most were nondescript forms, many were teardrops, and none were round forms. This marked dependence of shape on viscosity is understandable. As soon as a glass mass is disrupted into irregular forms, surface tension forces begin to contract each blob toward a spherical shape, while viscous forces resist this deformation. At very low viscosities the resistance to deformation is low, so the time required for contracting to a spherical shape is small compared to that required for cooling to a solidified state, and the shapes become shperical before they become rigid. At very high viscosities, however, the resistance to deformation is high, so the time required for contraction into a spherical shape is long, and a blob will solidify before it can become spherical.

In contrast to the primary shapes produced in the absence of significant aerodynamic pressures, as described above, the shapes produced when sizable aerodynamic pressures act on a glass drop are quite unlike any australite primary shape. The photographs of figure 11 illustrate six such configurations in base view (top row), side view (center row), and front view (bottom row). These configurations, of which hundreds have been produced, are typical of the shapes into which glass drops solidify when distorted by aerodynamic forces. A saucer-like concavity has been impressed into the front face of each configuration by the small excess in pressure at the stagnation point (p_s) over that at the base (p_b). Thus, as the front is pushed in, the softer portion in the center of the drop moves laterally to one side, producing a relatively flat, asymmetric protuberance. This flattened appendage, with its extended surface area and thinner dimensions, solidifies rather rapidly, leaving the base portion of the leeward side of the drop still nearly spherical. Aerodynamically distorted forms of this type were found at all viscosities investigated, from 0.2 to 280 poises; none were found when glass was ejected into the vacuum chamber. These forms definitely do not occur among the various figures of revolution, mostly spheres, that constitute the australite primary shapes.

Consequently, the primary australite spheres must have been formed under conditions where such molesting aerodynamic forces were absent.

Unlike the tektite forms found in Australia, many of the configurations found in Indochina are flattened (Lacroix, 1932). In our experiments wherein a mass of highly viscous glass was forcibly disrupted by aerodynamic pressures, a number of forms were observed which were rather similar to some indochinites. For example, flattened discs and flattened teardrops resembling certain indochinites were found in the high-velocity ejection experiments. Consequently, while the case is clear for the australites, it can not be concluded that the indochinites also were necessarily formed in the absence of significant aerodynamic forces. In view of the concentrated distribution of tektites in certain portions of Indochina (e.g., at one location in South Viet-Nam 51 tektites were found by Nininger (1961) within a period of 18 minutes), one might entertain the idea that a large mass of highly viscous glass was torn asunder by the severe aerodynamic forces associated with the atmosphere entry of large objects.

It is pertinent to determine from the present experiments just how small the aerodynamic forces must have been, in the case of the australites, to allow essentially undistorted spheres to form. Such determinations can be made from a knowledge of the air density ρ_∞, the velocity of ejection V_∞, and the smallest size of the glass drops recovered undistorted by aerodynamic forces. In presenting data from experiments of this type, it is customary to employ the Weber number, $We \equiv \rho_\infty V_\infty^2 R/\tau$, where R is the drop radius and τ the surface tension. This number can be converted directly to the ratio of aerodynamic to surface tension pressure, $(p_s - p_b)/(2\tau/R)$, either for the conditions of our experiments where the Reynolds and Mach numbers were such that $p_s - p_b = 0.9\ \rho_\infty V_\infty^2$, or for the conditions of hypervelocity flight where $p_s - p_b = \rho_\infty V_\infty^2$ (the dimensionless distribution of differential pressure $(p - p_b)/(p_s - p_b)$ around a sphere is essentially the same in hypervelocity flight as it is in subsonic flight). Our experimental results for glass of viscosity 2 to 3 poise, corresponding to the viscosity which produced configurations similar to australite primary shapes, are:

Incipient disruption of drop $We = 2.6$

Small distortion from spherical $We = 1.1$

These values are not greatly different from those of many previous investigations where nonsolidifying liquids, such as water and oil, were employed. As may be deduced from the data of Lane and Green (1956), the critical values of We for the disruption of water drops under transient conditions range from 2.2 to 4.9 (ibid., p. 189), which are consistent with our value of 2.6. It may be noted that under very steady conditions, such as with freely falling drops, the critical values of the Weber number for disruption can be, and are expected to be, several times greater. For example, Margarvey and Taylor (1956) under such circumstances obtained the value $We = 6.0$ for the condition of immediate disruption of freely falling drops. The value of We for 10-percent distortion from spherical shape (measured by the ratio of major to minor axes), as determined from the waterdrop experiments of Lane and Green (ibid., pp. 184 and 177) is about 1.3, and from those of Margarvey and Taylor is about 0.5. These values compare well with our value of 1.1, which corresponds to about 15-percent distortion of glass drops.

The experimental values for Weber number are fully concordant with theoretical considerations. The distortion from spherical shape can be large only if the mean disrupting external pressure differential $\overline{\Delta p}_{ext} \approx (p_s - p_b)/2$ of aerodynamic forces is comparable to or greater than the constraining internal pressure $\Delta p_{int} = 2\tau/R$ of surface-tension forces; thus the ratio $\overline{\Delta p}_{ext}/\Delta p_{int} \approx We/4$ is a measure of the amount of distortion. It follows that large distortions from a spherical shape would be expected for $We \approx 4$, or greater, in agreement with the experiments; and that small distortions would be expected when We is less than about unity, also in agreement with the experiments.

The foregoing experimental results impose very severe restrictions on the atmospheric environment at the site where the Australian tektites were formed and first heated. A multitude of primary australite spheres not only have escaped disruption, but have remained spherical; and it is certain that any atmosphere surrounding them during formation must have been sufficiently tenuous that the resulting aerodynamic pressure differential $\Delta p_{aero} = p_s - p_b$ was smaller than the critical amount for disruption. A simple calculation from the experimental value of $We = 2.6$, corresponding to incipient disruption, yields $\Delta p_{aero} < 2.3\tau/R$ for the Australian tektites. The larger australites correspond to primary masses of several hundred grams, and to values of $R \approx 3$ cm (Baker, 1962b, 1955). By substituting into the expression above the value $\tau = 360$ dynes/cm for glass of tektite composition (Morey, 1954, ch. VII, table VII.6) there results $\Delta p_{aero} < 300$ dynes/cm², or 3×10^{-4} atm. From the value $We = 1.1$ for small distortion of spheres, a somewhat more severe limit is obtained, namely, $\Delta p_{aero} < 1.0\tau/R$. As noted earlier, the primary shapes of the australite buttons were either spheres, or nearly spheres. The larger ones had radii of 2 to 2.5 cm (Baker, 1955), and at least one example is known of a perfectly developed australite with $R = 3.05$ cm (Walcott, 1898; Baker, 1961). These primary shapes could not have had even the small amount of distortion observed in the present experiments, since this distortion produced sphero-lenticular shapes which would be aerodynamically stable with the flattened side to the rear: no well preserved australite, to the authors' knowledge, exhibits a flattened base of this character. Consequently, an upper limit to the distorting aerodynamic pressure during primary formation is obtained from $\Delta p_{aero} < 1.0\tau/R$, $R = 3$ cm, and $\tau = 360$; namely, $\Delta p_{aero} < 2\times10^{-4}$ atm. This limiting value will be used in subsequent discussions as a criterion for judging whether or not various hypotheses of tektite origin are compatible with this aerodynamic requirement. Since $\Delta p_{aero} = \rho_\infty V_\infty^2$ in high-velocity flight, this limitation can be expressed in several different, though equivalent, ways:

Static pressure differential: $\Delta p_{aero} < 2\times10^{-4}$ atm (1a)

Dynamic pressure: $\rho_\infty V_\infty^2 < 200$ dynes/cm² (1b)

Acceleration: $a < 0.015$ earth g (1c)

where ρ_∞ is the gas density of the atmosphere surrounding the primary tektites during their initial flight, V_∞ is the velocity of motion relative to that gas, a is the maximum acceleration determined from Δp_{aero} and the tektite mass. The severity of requirement (1a) may be realized by noting, according to experiments we have conducted, that aerodynamic pressure differentials of greater amount can be produced by a breath of air blown from a man's mouth on a sphere some 20 cm distant.[2] We should not be surprised, therefore, at the conclusion deduced therefrom, that the primary australite spheres, which necessarily were somewhere given tremendous velocities in order to have overspread Australia, were first formed and solidified in a near vacuum.

In addition to the evidence from experiments on glass drops, some independent evidence from experiments on the ablation qualities of tektite glass provide a visual illustration substantiating the conclusion of tektite formation in a near vacuum. It is well known (e.g., Morey, 1954, pp. 87-91) that gases inevitably are dissolved in glasses during formation, and the presence of these dissolved volatiles can be forcefully illustrated by heating a glass to some high temperature, and then suddenly reducing the pressure: the glass froths, because the gases, which were dissolved at a formation pressure of one atmosphere, rapidly are liberated, in accordance with Henry's law of gas solubility proportional to pressure. Glasses can also froth extensively by ebullition if the pressure is reduced below that for boiling. In our ablation experiments the order of heating and pressure reduction is inverted, but the results are the same. We have conducted numerous experiments on terrestrial glasses, which were made at a pressure of one atmosphere or higher, by suddenly exposing the glasses to a low-pressure hypervelocity air stream. The region of lowest pressure under such conditions is at the base, where $p_b \approx 0.001$ atm. Formation of a circumferential flange creates a region of low base pressure behind the accumulated melt. In such a region, any dissolved gas can readily be liberated if present, or any bubble cavity can expand if its internal pressure exceeds the base pressure, or any ebullition can occur if the base pressure is lower than the boiling pressure corresponding to the local temperature of the flange melt. The result in each of these circumstances is a frothy flange, as illustrated by the post-ablation models in the top row of figure 12. They represent, from left to right, the remains of originally smooth models of impactite from the Henbury crater in Australia (obtained from the American Meteorite Laboratory), of borosilicate glass rod, of soda-lime marble, and of a synthetic tektite glass model. The frothing of the borosilicate and soda-lime glasses may be due to either liberated gases (from the furnace gases dissolved during manufacture at 1 atm pressure) or to boiling since neither of these glasses contained any visible internal bubbles before ablation. The frothing of the Henbury impactite and that of the synthetic tektite (made at 1800° C, at 1 atmosphere pressure) is partly attributed to the expansion of internal bubbles known to exist prior to their low-pressure ablation (p_s the order of 0.1 atm). In striking contrast to the frothy flanges produced on these known terrestrial glasses are the smoothly glazed, highly polished flanges produced on natural tektite glasses ablated under similar low-pressure conditions (bottom row of fig. 12). The rizalite specimen is from Pugad Babuy, Luzon, and the three australite specimens are from an area just south of the Mann Ranges in the northwest corner of South Australia. Occasional bubble imperfections are observed on the flanges of natural tektites. These imperfections sometimes form pits indicative of a bubble pressure lower than the exterior (e.g., the pit barely discernible on the lower portion of the flange of the rizalite in fig. 12), and sometimes bulges indicative of a higher pressure. In light of the result of Suess (1951) that the internal bubble

[2]These experiments were conducted by constructing a sphere of australite size imbedding pressure orifices at two opposite poles, connecting the orifices to a U-tube manometer, and noting the pressure differential $p_s - p_b$ created by blowing on the sphere.

pressure within natural tektites is less than 10^{-3} atm, it is believed that these flange bubble pits or bulges are indicative of the amount of vaporization that has taken place within the bubble as it traversed the distance from where it first appeared in the liquid layer, to where it finally rested in the flange melt. Inasmuch as the synthetic tektite glass which froths readily (see upper right model in fig. 12) has the same composition, and hence same boiling temperature as the natural tektite glasses that do not froth, it is deduced that the observed frothing on the synthetic tektite is indicative mainly of the liberation of the dissolved furnace gases which surrounded the terrestrial glass during its manufacture at one atmosphere pressure. The absence of frothing on the natural tektite shows that (1) the content of dissolved gases in tektites is very much lower than in terrestrial glasses, and that (2) the gas pressure surrounding the tektites during their formation also was very much lower than atmospheric pressure. The first of these deductions from ablation experiments is consistent with previous measurement of the quantity of gases released by heating tektites in vacuo (Beck, 1910, Lacroix, 1932, Suess, 1951, Friedman, 1958): the quantity of volatiles so expelled per gram of tektite glass is one to three orders of magnitude less than that expelled from typical terrestrial rocks. The second of these deductions is concordant with the experiments of Freidman, Thorpe, and Senftle (1960), who have presented evidence from the magnetic properties, and from the unusually low ferric/ferrous ratio of tektites, that they were formed by fusion at high temperature in an atmosphere whose partial pressure of oxygen was very much lower than that at the earth's surface.

It is not to be inferred from the absence of frothing on the natural tektite models illustrated in figure 12 that natural tektite glass never exhibits frothing. Since frothing can occur from the process of boiling, as well as from the release of dissolved gases, a natural tektite, or any other vacuum-made glass, will froth extensively if first heated to a high temperature and then subjected to a pressure much lower than the corresponding boiling pressure.

In summary of the results of the present section, it is concluded from experiments on the shape categories into which cooling glass masses solidify, from observations of the contrast in low-pressure ablation characteristics between terrestrial and tektite glasses, and, most important of all, from the remarkably small aerodynamic pressures which disrupt fluid glass drops, that the primary australites were formed and first fused in the environment of a near vacuum. The quantitative values for the upper limit on the surrounding atmospheric density depend upon the exiting velocity of flight, and this, in turn, depends upon the celestial object from which it is hypothesized that the australites might have come. Further discussion of this is given in a later section concerned with several of the individual hypotheses of tektite origin.

COMPARISON OF CALCULATED AND EXPERIMENTAL CHARACTERISTICS OF AERODYNAMIC ABLATION

In analyzing the transient ablation process wherein aerodynamic heating converts a primary tektite shape into a secondary one, some rather specialized analytical methods are involved, a number of detailed equations are encountered, and a high-speed digital computing machine is employed. Only qualitative features of the computation methods are described in the present section. An abridged discussion of the principal equations solved is presented in an appendix to this paper.

A number of papers have been written in recent years on methods of calculating the ablation characteristics of glass (e.g., Sutton, 1958, Bethe and M. Adams, 1959, Scala, 1959, Georgiev, 1959, Powers, Georgiev, and M. Adams, 1960, Hidalgo, 1960, E. Adams, 1961, Fledderman and Hurwicz, 1960). The various methods are basically the same in the sense that each follows the time-honored path of solving the three fundamental differential equations expressing conservation of momentum, mass, and energy for the flowing layer of viscous glass; they are different in the physical approximations made, the mathematical techniques used, and in the scope of physical phenomena considered. Various physical properties of the glass appear in the differential equations of conservation, and these important properties, of course, must be obtained from laboratory measurements on each glass composition investigated. Aerodynamic characteristics appear in the computations mainly as auxiliary equations prescribing the pressure, enthalpy, and heating rate at the stagnation point. The use of a digital computing machine enables the various differential and auxiliary equations to be solved simultaneously and rapidly. Two independent mathematical procedures have been machine programmed for solving the equations: one method utilizes an integral procedure of solving the energy equation (method I), whereas the other utilizes a finite difference procedure (method II). Both methods have been used in the researches cited above; and both provide satisfactory computational results.

Probably the most arduous task, and certainly one of the most important, in computing the characteristics of aerodynamic ablation, is the measurement at high temperatures of the physical properties of molten tektite glass. These properties can vary widely for different compositions of tektites, primarily because of the variation in silica content. Australites, for example, vary from about 65-percent to 80-percent silica, and even in a given location they vary almost as much (Baker, 1943, 1959). The most variable of the physical properties, the viscosity and the vapor pressure, are also the most important to the ablation computations. It is a fortunate circumstance, however, that the silica content of a given australite can be determined with adequate accuracy from readily measurable quantities, such as specific gravity and index of refraction; consequently, this information, together with that from an adequate number of measurements of the physical properties of tektite glasses with various silica contents, makes it possible for realistic calculations to be made of the ablation characteristics of any given australite. To achieve good accuracy in the computations, measurements over a wide range of temperatures have been made of the pertinent physical properties for various compositions of australite glass. Independent tests of the computation program have been obtained by measuring certain ablation characteristics which are sensitive to each physical property: thus, calorimetric data on thermal diffusivity have been tested by measurement of the striae distortion and of the rate of change of radiant energy emission during ablation; absorption data on opacity have been tested by measurement of the steady-state value of radiant energy emission during ablation; rotating cylinder data on viscosity have been tested by independent measurement of the stagnation-point recession during ablation; and vapor pressure data have been tested by measurement of the mass loss during ablation experiments. In the remainder of this section we shall see how various of the computed results, based on the measured physical properties (a typical set of which is given in appendix A), agree with the corresponding ablation measurements.

A comparison of calculated and measured values of radiant energy emission provides a test both of the data on thermal diffusivity (K), and on opacity (α). In the first few seconds of an ablation experiment, before melt flow occurs, the values of viscosity and vapor pressure are unimportant, and the time rate at which the wall temperature T_W increases depends primarily on K and α. In our experiments the flux of radiated energy E_r was measured; and this determined the brightness temperature T_b through its definition $E_r \equiv \sigma T_b^4$, where σ is Stefan's constant. The computation methods calculate T_W and the temporally varying emissivity ϵ, so that the radiation equation $\sigma \epsilon T_W^4 = E_r = \sigma T_b^4$ enables a brightness temperature to be computed. In figure 13 the calculated values of brightness temperature are compared with measured values on a synthetic tektite glass model (STG 1-H, $0.76SiO_2$, $\rho = 2.405$) and on an Australian tektite model (A 231, $\rho = 2.429$; originally a 10 gm elongate core from Nullarbor Plain). Several other models, of both synthetic and natural tektite glass, were also investigated and found to yield values for $T_b(t)$ intermediate between the two sets of data shown here. The calculations correspond to the physical properties of the synthetic tektite glass; and their good agreement with the experiments is evident. After about 7 or 8 seconds, steady state is attained and $T_b = T_b(\infty)$. If these data are plotted in the form $T_b/T_b(\infty)$ versus time -- a form in which K is important but α is not -- the calculations and experiments would closely agree; this shows that the thermal diffusivity used in the computational program is in accord with experiment. The fact that the computed $T_b(\infty)$ values also agree with measured values shows that the opacity and internal radiation calculations also are in accord with experiment.

A comparison of calculated and measured rates of recession for aerodynamic conditions wherein ablation occurs dominantly by melting, and insignificantly by vaporization, provides a test of the data on viscosity. In figure 14 calculated curves for methods I and II are compared with experimental values for models constructed from two australites (AA10 from Northwest corner of South Australia; A152, 10 gm core from Nullarbor Plain), one rizalite (R258, 18 gm specimen from Pugad Babuy, Luzon), and a synthetic tektite glass - all having about the same silica content of about 71 percent as judged from the specific gravities listed in figure 14. It is clear from this figure that the synthetic tektite glass ablates at the same rate as natural tektite glass of the same chemical composition, that there is little difference between the two computation methods, and that the calculated rates of ablation are in good agreement with the experiments. The calculated amount of ablation is a little greater than measured at the beginning of the runs and a little smaller at the end, partly because of the use of a constant average value for R_F in these particular computations, rather than a value that increases at first and then decreases. Agreement of this nature has also been found for a wide variety of glass compositions, as may be seen from figure 15. Here results are presented for a lead glass, for three different synthetic tektite glasses (65-, 75-, and 80-percent silica), and for pure fused silica. The viscosity of these glasses increases in the order mentioned, and the ablation rate decreases in consonance with the increase in viscosity. The agreement between calculation (method I) and experiment is quite satisfactory for the three synthetic tektite glasses. These particular glasses were made by the Corning Glass Co. of New York to composition specifications designed to represent the composition range covered by the Australian tektites. Chemical analyses of the synthetic tektite glasses, made at the U. S. Geological Survey and sent to us by Drs. E. C. T. Chao and F. Senftle, agreed closely with previous analyses of australites of the same silica content. The significant difference in the rate of ablation between the different tektite glasses, amounting to a factor of about 2:1 at $t = 10$ sec, demonstrates that one set of physical properties cannot provide an accurate basis for computing the amount of ablation of all tektites. Consequently, in determining australite entry trajectories, and hence their location of origin, each tektite which has been ablated a given amount and which was originally a primary sphere of a given radius, is analyzed individually in accordance with its particular silica content and its particular physical properties.

A good agreement between calculated and measured rates of ablation has also been found for test conditions other than those of figures 14 and 15. Ablation rates have been measured at stagnation pressures from 0.05 to 1.3 atmospheres, at enthalpies from 700 to 6000 cal/gm (V from about 2.5 to 6.5 km/sec), and have exhibited similar agreement with computations. It may be noted here that the pressure range investigated covers that encountered by objects of australite size for entries up to about 14 km/sec, and that aerodynamic heating experiments at $V = 6.5$ km/sec corresponds to peak heating conditions during an entry with initial velocity V_i of about 8 km/sec.

Further comparison of the computational and experimental results has been obtained from measurements of the displacement of glass striae just beneath the ablated front face. Thin sections already have been presented in figure 6 from which measurements of the displacement d, as a function of depth y beneath the surface, have been made for various distances x from the stagnation point. The results are compared with calculations in figure 16. Various data points correspond to various pre-ablation distances s of the striae from the stagnation point, the latter being determined with aid of the striae themselves as the junction point on each side of which the striae are displaced in opposite directions. It is to be noted that some of the thin sections purposely have been photographed out of focus (e.g., right portion of figure 6) in order to make the striae more readily visible. In conducting measurements of $d(y)$, however, only focused photographs were employed to avoid distortion. For the test condition of figure 16, and for this particular model (IC 202-2), the value calculated for the characteristic thickness δ of the fluid glass layer is 0.010 cm. The dotted line in figure 16, representing the computed striae displacement function at the stagnation point ($s = 0$), is seen to agree fairly well with the measured displacements for striae near the stagnation point (e.g., $s = 0.11$ cm). The striae farther away from the stagnation point (e.g., $s = 0.47$ cm) correspond to somewhat greater values of δ. This trend is to be expected in view of the decrease in heating rate with increase in distance from the stagnation point.

A determination of the vapor pressure has been made by measuring in a furnace the initial time rate of mass loss of tektite glass relative to that of silica glass. These measurements were conducted in an atmosphere of argon at reduced pressure, and at various temperatures from 2100° to 2500° K. Since the vapor pressure of silica is known, knowledge of the relative mass loss provides vapor pressure data for tektite glass. The mass loss from australite samples was always greater than that of the silica, by a factor of from about 2 to 3.5, thereby indicating a correspondingly greater vapor pressure. An independent test of these data has been conducted by measuring the mass of tektite models before and after aerodynamic ablation in the arc jet. Here again silica models were used as a standard of comparison. The change in mass for runs of about 10 seconds duration was the order of 0.001 gm for a typical tektite glass; this small mass loss could be measured and repeated on different runs, to within an accuracy of about ±0.0002 gm. The furnace mass loss data, and that calculated for the aerodynamic ablation experiments, were in reasonable agreement. A confirmation of the calculated mass loss during ablation is important to the deduction of entry trajectories, since it means that the heat absorbed and, more important, the heat blocked by the vaporization process, are placed on a foundation substantiated by experiments.

As a final indication of the accuracy with which the aerodynamic ablation of glasses can be computed at present, and has been computed in the past, reference is made to an atmosphere-entry flight test reported by Hidalgo and Kadanoff (1959). This particular vehicle was protected by a heat shield of silica glass. By substituting into our transient ablation program for tektites the particular physical properties of silica, the particular trajectory conditions of this entry, and the m/C_DA value for this vehicle, the calculated amount of ablation at the stagnation point, compared to the actual amount, was found to be 8 percent less according to method I and 11 percent more according to method II. By way of comparison, the calculations of Hidalgo and Kadanoff, which were based on quasi steady-state ablation analysis, overestimated the amount of ablation by 10 percent.

It is pertinent to note in this connection that the initial atmosphere entry analysis for australites (Chapman 1960) was based on essentially the same analytical method as that used by Hidalgo and Kadanoff. It was also based on estimated physical properties for tektite glass, and on simplifying approximations for the R_F and m/C_DA variations; and for these reasons the accuracy of entry velocities determined therein was stated to be within about ±2 km/sec. The recent ablation calculations of E. Adams and Huffaker (1962), who have employed a different estimated set of physical properties, and a different set of simplifying approximations for the R_F and m/C_DA variations, are similarly limited to this order of accuracy. With more complete data on physical properties of Australian tektite glass now available, however, and with the experimental verification of the ablation characteristics of tektite glass now established, the entry velocities of the Australian tektites have been recomputed with improved accuracy. While the net improvement over the original calculations is substantial (believed to amount to a factor of about two in accuracy), it is not in full proportion to the increase in effort expended: the present calculations are based on two years effort by several individuals, rather than several months effort by one; the present system of equations to which solutions are obtained fill pages, rather than a few lines; and the final product, the numerical values for entry velocity, is obtained with an IBM 7090 high-speed electronic digital computer, rather than with a slide rule. The principal accomplishment of these efforts is that the analytical methods from which determinations are made of the australite entry trajectories and, hence, of the location of australite origin are now placed on a firm experimental foundation; and scientists from disciplines other than atmosphere-entry aerodynamics now are provided with a clearer view of the substance behind the aerodynamic evidence pertaining to tektite origin.

DETERMINATION OF ENTRY TRAJECTORIES

In an earlier paper (Chapman 1960) it was shown that the amount of ablation y_s and the distortion of striae $d(y)$ each lead to an independent condition on the initial velocity V_i and angle γ_i of an entry trajectory. A point of compatibility exists between the two conditions, as determined by the intersection of their respective curves in $V_i(\gamma_i)$ coordinates, and this point fixes the entry trajectory. In the two years following this paper, we have conducted numerous ablation experiments with tektite glass, and have found that an additional independent condition on $V_i(\gamma_i)$ is provided by the presence of, and spacing between, ring-wave flow ridges. This finding is especially significant because thousands of tektites remain sufficiently well preserved to still exhibit adequate data on ring-wave spacing, whereas only one tektite (No. 279 of Baker Collection, figured in plate X of his monograph) thus far has been shown to exhibit adequate data on striae distortions. Thus, the possibilities of determining entry trajectories of the australites, and a few of the Javanites, are greatly enlarged by the new results.

The relative spacing between ring-wave flow ridges depends primarily on the stagnation-point pressure p_s, which, in turn, depends on the entry trajectory. At sufficiently low pressures, tektite glass ablates without producing any ring waves: photographs of four models illustrating this behavior already have been presented in figure 12. The three australites in this figure for example, show no ring waves and were ablated at $p_s \approx 0.08$ atm. As p_s is increased, ring waves appear first with a rather wide spacing, and then, upon further increase in pressure, with a progressively closer spacing. This trend is illustrated in figure 17 by the four relatively small models in the top row, ordered from left to right in increasing pressure; by the four larger buttons in the middle row similarly ordered; and by the three models in the bottom row. Ring waves are entirely absent on the models with $p_s = 0.21$ atm in the top row, 0.14 atm in the center row, and $p_s = 0.085$ and 0.11 atm in the bottom row. It is to be noted that the two models at the right of the bottom row were ablated at the same enthalpy, namely, $h_s = 1150$ cal/gm, and reveal the same marked dependence of ring-wave spacing on pressure as do the various other models that happen to have been ablated at different enthalpies. Systematic variations in both enthalpy h_s and pressure p_s revealed h_s to be a minor and p_s to be the major variable upon which the wave diameter D_w depends. Consequently, the data on diameter of the first ring wave D_{w_1} have been plotted in figure 18 as a function of p_s without discrimination as to individual variations in h_s. These data represent the results of approximately 70 experiments wherein the enthalpy was progressively varied from values well above to values substantially below that at which ablation terminates. The models employed were of typical australite size (D from 1 to 3 cm). It is noted that D_{w_1} is normalized with respect to the model diameter D, in order to facilitate the identification of models without ring waves, namely, by the simple condition $D_{w_1}/D > 1$. Such models are represented in figure 18 by cross points plotted with upward directed arrows at $D_{w_1}/D = 1$. For $p_s < 0.075$ atm no ring waves were found; for $0.075 < p_s < 0.25$ atm ring waves were sometimes observed, and sometimes not, depending on h_s and D; and for $p_s > 0.25$ atm, ring waves always were observed on models of typical australite-button size. It is clear that a knowledge of ring-wave spacing, as represented by the first wave diameter D_{w_1}, gives information on the final value of stagnation pressure p_{sf} existing just prior to the termination of ablation.

The computed variation of several physical quantities of interest during a typical australite entry is illustrated in figure 19. These curves correspond to the average of results calculated by methods I and II for a primary sphere of $R_B = 1$ cm entering at $V_i = 11.2$ km/sec (earth escape velocity), at $\gamma_i = 20^o$, and possessing the physical properties listed in the appendix for the average Port Campbell australite containing about 76-percent silica ($\rho = 2.40$ gm/cm^3). As time progresses during the entry, the surface temperature T_w at the stagnation point increases, and ablation begins when $T_w = 2200^\circ$ K is reached. The surface temperature continues to increase to a maximum of 2720° K, and then falls when the velocity V drops below values which can sustain this temperature. Ablation terminates when $T_w = 2000^\circ$ K, beyond which point the total amount of ablation y_s and the portion thereof that has vaporized y_{sv} both remain constant. The final amount of ablation is designated as y_s in subsequent figures, and the stagnation-point pressure which existed just prior to the termination of ablation, as computed from the air density and flight velocity is designated as p_{sf}. It is to be noted from figure 19 that the ablation proceeds mainly by melting, rather than by vaporization. At the stagnation point the fractional ratio of mass vaporized to total mass removed, y_{sv}/y_s is seen to be about 0.25. Over the circumferential areas situated away from the stagnation point, the temperatures would be lower than at the stagnation point, and the vaporized fraction would be smaller. Thus the average fraction vaporized for the entire tektite would be considerably less than the fraction computed for the stagnation point.

It is pertinent to illustrate the manner in which an entry trajectory can be established from knowledge of the amount of ablation y_s, and of the final ablation pressure p_{sf}. The results of some example calculations are presented in figure 20 for a typical Port Campbell australite; namely, $R_B = 1$ cm and $\rho = 2.40$ gm/cm^3. These results also are based upon the average of calculations from methods I and II. Each curve in the left portion of this figure represents a constant value for y_s and the domain for negligible ablation is conveniently illustrated on such a plot. It may be noted here that the 5 km/sec upper boundary on velocity for negligible ablation agrees fairly well with the 4- to 6-km/sec boundary previously calculated (Chapman, 1960) by a much simpler method. In the right portion of figure 20, each curve represents a constant value of p_{sf}, and the domain for no ring waves ($p_{sf} < 0.075$ atm) is conveniently illustrated in such a plot. As the entry velocity V_i is increased, both the ablation y_s and the pressure p_{sf} increase, as would be expected. As the entry angle is increased, and the descent becomes steeper ($\sin \gamma_i = 0$ corresponds to horizontal entry, and $\sin \gamma_i = 1$ to vertical), the pressure increases, but the amount of ablation decreases: the steeper entries involve a shorter duration of heating, which more than compensates for the accompanying increase in pressure. At entry velocities less than about 5 km/sec, the ablation would be negligible, and such trajectories, of course, are excluded as possible australite entry trajectories; similarly, at very shallow entry angles ($\sin \gamma_i < 0.14$, $\gamma_i < 8^\circ$), the pressure is too low ($p_{sf} < 0.075$ atm) for ring waves to form, and these trajectories also are excluded. A glance at the opposite inclinations of the two sets of curves in figure 19 reveals that for a particular y_s and a particular p_{sf}, the two curves would intersect at a point which determines both V_i and γ_i, and, therefore, the entry trajectory of the tektite. In practice, however, the determination of y_s for a given tektite is not exact, the calculation of $V_i(\gamma_i)$ for a given y_s is not perfect, and a given ring-wave spacing corresponds to a range in pressure, rather than to a single pressure. Consequently, in the applications herein, the y_s and p_{sf} lines each become bands, and their intersection becomes a zone, somewhere within which would be the true V_i and γ_i.

In analyzing the amount of ablation on the australite primary shapes, which constitute various figures of revolution, four complications must be given consideration: (1) an axially symmetric configuration which can fly stably in only one attitude relative to the flight path -- such as a teardrop, or a round form with an internal bubble displaced off center, or a sizably oblate spheroid, or an elongate form -- generally cannot be expected to have entered the atmosphere at exactly that attitude required for stable flight, and must be expected to have turned, or wobbled, or perhaps to have tumbled, in the early and pre-ablation stages of entry; (2) some of the axially symmetric round forms may have been significantly oblate spheroids, rather than perfect spheres; (3) prior to entry, some of the primary tektites may have been slowly turning about an axis inclined to the flight path direction; and (4) some of the tektites which today exhibit a thoroughly bubbled pitted posterior surface, may have been shrouded with a shell of glass froth prior to their entry into the earth's atmosphere. By restricting attention to the perfect button variety of tektite, some of which can be shown to possess a complete "first-and-only" flange (e.g., see fig. 9) and which can be proven to have been of nearly spherical primary shape, the first two of these complications automatically are avoided. Also, by considering a sufficient number of such australites the third complication is circumvented. The Port Campbell australites, as noted by Baker, generally exhibit a bubble-pitted base of texture entirely different from the smooth-surfaced flange surrounding it. Thus the pitting may be partly original and partly due to terrestrial etching. Such pitting is to be expected for formation of primary shapes in a near vacuum: boiling temporarily would occur at the surface, though not necessarily in the interior which is slightly pressurized by surface tension. The abundance of pits with relatively sharp edges show that the melting has not occurred on the base, and that the base has not faced upstream during the ablation phase of entry. There appear to be few exceptions to these characteristics. Hence, by considering a number of round-form, perfect-button tektites, we can be assured that any pre-entry turning, which might be important on an occasional tektite that happens to have had some initial rotation about an axis perpendicular to the flight path, is of minor importance in determining the amount of ablation on most of them. For the results to be presented subsequently, the possible effect of pre-entry turning, as well as the possible effect of the presence of a pre-entry shell of glass froth, would be to increase somewhat the calculated velocities of australite entry.

A significant feature exhibited by the australite buttons is their wide variance in apparent amount of ablation. This feature has been previously emphasized by Baker (1959, p. 73). For a nearly spherical primary shape, the amount of ablation is readily deduced from the equation $y_s = 2R_B - D_e$. Values of y_s have been tabulated by Baker (1962a) for 23 perfect buttons from the single site of Port Campbell, Victoria; they vary from 0.55 cm for P.B. 16 (perfect button number 16 in Baker's tabular data) to 1.65 cm for P.B. 5. Such a large variation is not to be ascribed to differences in silica content, inasmuch as buttons with the same specific gravity show a similar variation (cf., $y_s = 0.55$ cm for P.B. 16 having $\rho = 2.394$, and $y_s = 1.40$ for P.B. 18 having $\rho = 2.395$). Also, this variation is not to be attributed to differences in initial radius, inasmuch as buttons with the same initial radius show significant variations (cf., $y_s = 0.56$ for P.B. 1 having $R_B = 1.03$, $\rho = 2.373$, and $y_s = 0.99$ for P.B. 9 having $R_B = 1.05$, $\rho = 2.377$), and inasmuch as variations in R_B have only a very small effect on the calculated y_s. This latter result may seem strange at first, but is to be expected since both the heating rate and the total heat absorbed per unit area by laminar convection during entry vary as $\sqrt{m/C_D A R}$ (see, e.g., Chapman, 1959), and

m/C_DAR, which is equal to $4\rho/3C_D$ for solid spheres, is independent of R. It is for this reason that y_s, rather than the volume or mass percent of ablation, is the fundamental quantity characterizing the amount of ablation. The sizable variations exhibited by y_s are therefore significant and will lead to considerable variations in the $V_i(\gamma_i)$ curves deduced for the various australite buttons. If the australites are cosmic in origin V_i for direct entry would be essentially constant for all, and the sizable variation in y_s for tektites from the same site must be accounted for either by such circumstances as entry at different angles at different times (due to the earth's turning while a large cluster lands), or by the existence of mainly oblate spheroids rather than spherical primary shapes. If the australites are terrestrial in origin, the flight range from their location of origin to that of their common landing place must be constant, and the y_s variations are to be accounted for either by such circumstances as the permissible variance in V_i and γ_i consistent with a constant range, or by the prevalence among the primary shapes of sizably oblate, rather than of nearly spherical, spheroids. We shall examine these circumstances in greater detail subsequently, to see which ones are compatible with the over-all evidence.

It is of interest to demonstrate how the stria distortions in the thin melt layer depend markedly on the rate of aerodynamic heating q_s. Two thin sections illustrating this are presented in figure 21. Both models were fabricated from one Indochina teardrop (IC202, originally an 18 gm teardrop from Dalat, South Viet-Nam), and both were ablated for about 7 seconds - but at considerably different heating rates: that on the left with larger flange was ablated at $q_s = 156$ cal/cm^2 sec, and that on the right with smaller flange at $q_s = 90$ cal/cm^2 sec. It is apparent from the systematic striae distortions that the thickness of the melt layer is smaller for the larger rate of heating, as it should be according to ablation calculations. Thus, entry at high velocity and steep angles encounters much greater heating rates and thinner melt layers than entry at small velocity and shallow angles; and a comparison of the observed striae displacements $d(y)$ on a given tektite with those calculated for entry at various V_i and γ_i enables a zone of compatibility in $V_i(\gamma_i)$ coordinates to be delineated. Somewhere within this zone the entry conditions are to be found.

Proceeding now with the determination of entry trajectories for various tektites, we start with australite B279 (number 279 of Baker's collection). The principal characteristics of this tektite are included in the following table of australites, the entry trajectories of which are computed in the present paper:

Designation	ρ, gm/cm^3	R_B, cm	R_F, cm	$\frac{D_{w1}}{R_F}$	y_s (= $2R_B - D_e$), cm	Collection and location of find
B279	2.371	1.10	1.36	0.99	0.90	Baker; Port Campbell, Victoria
P.B. 1	2.373	1.03	1.36	.64	.56	Baker; Port Campbell, Victoria
P.B. 4	2.391	1.12	1.28	.76	1.0	Baker; Port Campbell, Victoria
P.B. 6	2.397	1.23	1.23	1.04	1.33	Baker; Port Campbell, Victoria
B890	2.372	1.38	1.66	1.03	.32	Baker; Port Campbell, Victoria
C625	2.424	.92	1.19	.92	.50	Cassidy; Charlotte Waters, N.T.
Au9	2.441	.90	1.19	.78	.59	Cassidy; Mt. Monger, W.A.

As previously mentioned, australite B279 is the only tektite for which data has been obtained on the distortion of internal striae $d(y)$, as well as on the amount of ablation and on the spacing of ring waves. For this australite, the characteristic thickness of the liquid layer is $\delta = 0.01$ cm (see fig. 7). The two dashed curves in the left portion of figure 22(a) correspond to the range between $\delta = 0.008$ and $\delta = 0.012$, a range that allows for realistic uncertainties in the accuracy of determining δ. We see that the zone between the two curves deduced from the values of p_{sf}, which are compatible with the first ring-wave diameter $(D_{w_1}/R_F = 0.99)$, follows a trend similar to that deduced from δ but is somewhat displaced. The zone between the two curves obtained from the apparent amount of ablation $(y_s = 2R_B - D_e = 0.90$ cm), however, follows an opposite trend. The higher curve of these latter two represents method I, and the lower method II, which we expect from the comparison with flight data mentioned earlier to underestimate and to overestimate, respectively, the amount of ablation. The crossing curves delineate a certain zone of intersection wherein all three sources of data are mutually compatible. This zone lies in the entry velocity range around 11 km/sec, and at an entry angle of about 12° from the horizontal $(\sin \gamma_i \approx 0.2)$. Australite B279 was one of the specimens for which the original entry calculations (Chapman, 1960) indicated a velocity of between about 10 and 12 km/sec and an angle between about 5° and 10°. In comparison to these earlier results for australite B279, the present results, wherein data on ring-wave spacing are considered and wherein much more elaborate calculation methods are employed, are seen to be in reasonable agreement.

In the right portion of figure 22(a) are shown the entry zones determined for three of Baker's perfect button australites. Each zone is demarked by a boundary at the top left obtained from y_s and computation method I, and at the bottom-right obtained from y_s and computation method II. The bottom left and top right boundaries to the zone are obtained from ring-wave spacing and the corresponding range in p_{sf}. In a few cases the ring-wave sculpture is such that the first wave clearly is either in the early stages of development when it forms a bump rather than a crest, or in the later stages where it is about to become a second ring wave and surrounds a central hump. Experience has shown that in such cases the first wave safely can be regarded as corresponding to either the first half, or the second half, respectively, of the ring wave cycle. Australites of this type, for example, are P.B. 1 and C625. Each of the zones for perfect buttons demarcated in figure 22(a) is representative of more than one australite: thus, the domain for P.B. 1, with $y_s = 0.56$, is similar to that for three other perfect buttons exhibiting relatively small amounts of ablation (P.B. numbers 3, 7, and 16, with y_s between 0.55 and 0.65 cm); also, P.B. 4 with $y_s = 1.0$ cm is similar to five others exhibiting a medium amount of ablation (P.B. numbers 2, 9, 13, 14, 15 with y_s between 0.9 and 1.1 cm); and P.B. 6 with $y_s = 1.33$ cm is similar to four others exhibiting a relatively large amount of ablation (P.B. numbers 8, 18, 20, 21 with y_s between 1.3 and 1.4 cm). The rather large variation in entry velocities and angles deduced for these australites, all of which were found at one site, is a circumstance which commands careful consideration in comparing these entry trajectories with various hypotheses as to the origin of the australites.

Australite buttons from areas other than Victoria reveal ablation features similar to those on the Port Campbell tektites, and correspond to entry conditions that are not greatly different. One such example is australite Au9, from Western

Australia, the entry conditions for which are depicted in the left portion of figure 22(b). Also shown are the entry conditions for australite C625, from Charlotte Waters, near the northern boundary of the central portion of the Australian strewnfield. This latter button exhibits the smallest amount of ablation ($y_s = 0.50$ cm) of all the solid australite buttons of comparable size for which we thus far have obtained detailed measurements. Tektite B890 exhibits an amount of ablation that is still smaller, but this is attributable to a large, asymmetrically disposed, bubble cavity which it contains (a cavity reduces m/C_DAR, the heat absorbed, and the amount of ablation). In the case of B890 the y_s value is 0.32 cm, as determined from an average between values deduced by geometric reconstruction from an off-center section profile (kindly provided by Dr. George Baker), and by numerical integration of the flange volume as deduced from the cross sectional area of the flange. The value of 0.32 cm for y_s is the smallest of any australite, solid or hollow, that we have thus far studied. As noted earlier, any configuration, such as an asymmetric hollow tektite, that has only one attitude for stable flight, can not be expected to have entered the atmosphere at precisely the proper attitude for aerodynamically stable flight: on such australites someititial turning, or twisting, or wobbling into the aerodynamically stable position undoubtedly took place during the early stages of entry. In the process of turning, the stagnation point wanders over the surface of the tektite, distributes the heating over a greater area, and results in considerably less ablation than in the case of a nonturning tektite (such as a uniform sphere which is properly oriented for stable flight no matter what attitude it possesses prior to entry). It is unrealistic, therefore, to compute the entry velocity of tektites, such as B890, which can fly in only one attitude, under the assumption of zero turning and perfect aerodynamic orientation throughout entry. In the appendix to this paper some details are given of the computational method employed to account approximately for the turning which is expected during the early stages of entry of such tektites. Those portions of the domain boundaries represented by dashed lines in figure 22(b), correspond to the extension in the calculated entry conditions brought about by turning. It is seen that, when turning is disregarded, the V_i range for B890 extends only from about 7 to 10 km/sec; but, when turning is considered, V_i extends from 7 to about 13 km/sec. Complications introduced by the uncertain amount of turning constitute valid reasons for selecting the perfect button australites, rather than asymmetrical forms, for subsequent discussion of the entry conditions of the Australian tektites.

It is of interest to illustrate also the approximate entry conditions for tektites from Java. Unlike the primary australites, the primary javanites were of relatively irregular form; hence, the deduction of their entry conditions is subject to a considerable uncertainty in estimating y_s, as well as to an uncertainty in estimating the expected effect of turning on such irregular shapes. Entry calculations for the javanites also involve some uncertainty in the appropriate physical properties to use (especially vapor pressure) inasmuch as our experiments were conducted on australite glass of a somewhat different composition. Nevertheless, the approximate entry condition for two examples have been computed: (1) a 11.4 gm core, specimen J1, for which the estimated y_s is 0.58 cm, the ring wave spacing is $D_{W1}/R_F \approx 0.85$, and the initial radius is taken as 1 cm (this core has been figured by von Koenigswald (1960, figures 6(a) and 6(b)); and (2) a smaller core, specimen J2, representative of the size which is marginal for the production of ring wave flow ridges. Studies of various small cores in the collection of von Koenigswald revealed that $R_B \approx 0.6$ cm, $y_s \approx 0.29$ cm, and $D_{W1}/R_B \approx 1.0$, divided the smaller tektites without flow ridges from those with flow ridges. For both specimens the physical properties were taken as those of an australite with $\rho = 2.46$ (the value of ρ for J1, as communicated to us by G. H. R. von Koenigswald). The computed domains for atmosphere entry of J1 and J2 are shown in the right portion of figure 22(b). As in the case of B890, the domain boundaries represented by dashed lines correspond to the effect of turning on the calculated entry conditions. It is worthy of note that the flow ridges on the smaller javanites generally form an arc on one side of the front face, rather than a central ring, thus suggesting that some turning still existed even at the termination of ablation. In consideration of these circumstances, together with the several uncertainties introduced by the irregular shapes of the primary javanites, about all that can be deduced from the computed results for J1 and J2, is that the javanite entry velocity would be in the range between about 7 and 12 km/sec. Thus, as in the case of australite B890, the entry trajectories for the javanites involve considerable uncertainty, and are not of comparable accuracy to the trajectories determined for the perfect button australites, which are considered in greater detail subsequently.

HYPOTHESES OF TEKTITE ORIGIN

Some very significant experimental evidence pertaining to the mechanism of formation of tektites has been published recently by Chao, Adler, Dwornik and Littler (1962). They have discovered perfectly spherical metallic inclusions of near meteoritic composition completely embedded within certain tektites from the Philippines. The spherules range in size from 0.1 to 0.5 mm, shine in reflected light with a metallic lustre, and are free of any trace of oxidation. Their composition was found to consist mainly of kamacite, a phase of iron (about 95 percent) and nickle (up to 3 percent), which is a composition approaching that of iron meteorites. Chao, et al., have noted that similar spherules, though smaller, are abundant in the terrestrial impact glasses found near the meteoritic crater of Al Hadida (Wabar). Many years earlier, Spencer (1933a) reported the observation in australite and indochinite microsections, of a few imbedded spots also showing a metallic lustre by reflected light. Although these inclusions were not chemically identified, Spencer noted that they were of similar dimensions and of the same appearance as the metallic spherules which he had previously observed in the terrestrial impact glasses from the meteoritic craters of Wabar and Henbury. Consequently, Spencer (1933b) surmised that tektites originated from the impact of an iron meteorite in earth rock. This suggestion, that hypervelocity impact from a meteorite was the machanism which formed the tektites, is now given added experimental support by the petrologic evidence of Chao and his colleagues; but Spencer's assumption that the earth was the planet on which that impact took place, is contradicted by (1) the ballistic experience of past generations which has established that small objects flying through the atmosphere from a single location cannot possibly overspread an area the size of the Australian continent; (2) the aerodynamic experiments with masses of fluid glass ejected into the atmosphere, as described earlier, which demonstrate that the australite primary shapes were formed in an essentially atmosphereless environment; and (3) the aerodynamic ablation experiments of the past two years which, as explained later, establish entry trajectories for the australites that are uniquely compatible with origin from the moon, rather than the earth. In subsequent portions of the present section a discussion is presented of various hypotheses of tektite origin with emphasis on the several sources of aerodynamic evidence.

One conclusion from the experiments on the breakup of glass drops -- which is pertinent to the origin of tektites, irrespective of whether from a terrestrial or an extraterrestrial source -- is that it is possible for two different groups of tektites, such as those in Australia and in Indochina, to have grossly different primary shapes, and yet be congenetic from a single impact. The variance of primary shapes between strewnfields is indicative of different viscosities of formation, as Beyer (1942) previously has emphasized. In contrast to the australites, the indochinites are largely teardrops (Lacroix, 1932). Different portions of the ejecta from an impact necessarily would be expelled at different temperatures; that expelled from the first and most intense stage of shock propagation through the target crust would have a higher temperature than that expelled from later and less intense stages of propagation. The variation in temperature of tektite glass required to increase the viscosity by a factor of 12, which as shown earlier, is sufficient to produce shapes that are largely teardrops instead of spheres, is about 500° C. Since this difference in temperature is relatively small compared to the several thousand degrees produced during impact, and since fused ejecta from an impact vary in velocity as well as in temperature, it is clear how one event could produce a conglomeration of ejecta, both fragmented and fused: the higher temperature portion of the fused ejecta -- in the absence of molesting aerodynamic forces -- would produce largely spheres, a somewhat lower temperature portion, largely teardrops, and a still lower temperature portion, largely irregular shapes. Hypervelocity impacts, though, normally produce a mass of ejecta which is many times greater than that of the projectile, as shown, for example, by Denardo (1962). Hence, if the impact were on earth, there should be found somewhere the remains of a large quantity of ejecta produced concurrently with the tektites. If the impact were on an extraterrestrial body such as the moon, the principal quantity of ejecta would have remained there. For a typical meteoritic projectile impacting on the moon, some of the debris would escape the moon. Under such circumstances it is envisioned that the escaping debris would contain some ejecta of the fused variety, of widely different viscosity, which would rapidly solidify into myriads of glass objects of different primary shapes.

<u>Origin from terrestrial impact</u>.- The hypothesis that tektites originated when some cosmic body collided with the earth, was first suggested by Spencer (1933). In recent years this suggestion, in various modified forms, has been supported extensively by Urey, 1955, 1957; Barnes, 1961; Cohen, 1961 and Gentner, Lippolt, and Schaeffer, 1962. As one criticism of this hypothesis, some scientists (e.g., Nininger, 1943) have pointed to the experience of ballistics that atmospheric retardation at hypervelocities is tremendous and, consequently, restricts severely the flight range of small objects. Such restriction leads to the inevitable consequence that the spread of objects as small as tektites from coast to coast over Australia is not to be attributed to the flight of terrestrial impact debris through the atmosphere. In recognition of this criticism, advocates of a terrestrial impact origin for tektites have invoked the assumption that somehow much of

the earth's atmosphere was removed during the impact phenomenon, thereby enabling the fused earth initially to fly through a near vacuum, subsequently to solidify into primary forms in outer space, and finally to re-enter the atmosphere over Australia.

The extent to which the earth's atmosphere must be depleted to enable a relatively small tektite glass sphere of 1-cm diameter to exit from the atmosphere with a velocity compatible with the areal distribution of the australites has been determined from numerical solutions of the ballistic trajectory equations. Exponential atmospheres of varying sea-level density ρ_o were investigated, and the calculations carried out on an IBM 7090 electronic digital computer. Various initial velocities, V_o from 1 km/sec to 20 km/sec, and initial angles, γ from 5^o to 45^o relative to the horizontal, were considered in the calculations. It was found that, even with ejection at the optimum angle for maximum range, and at velocities up to 20 km/sec, the tektite would travel only a few hundred meters in the standard earth's atmosphere (ρ_o = 0.0012 gm/cm^3); only a few kilometers if 90 percent of the atmosphere were depleted (ρ_o= 0.00012 gm/cm^3); and about 30 km if 99 percent were depleted (ρ_o = 0.000012 gm/cm^3). If 99.9 percent were somehow removed, however, a swarm of rigid glass spheres of 1-cm diameter could manage to escape with the velocity requisite for spreading over an area comparable to that of Australia; but, in so doing they would be subjected to aerodynamic pressures -- in this reduced density of 10^{-3} atmosphere -- of about one atmosphere pressure differential from stagnation point to base. Such a pressure differential is several thousand times greater than a molten blob of tektite dimensions can withstand without disruption (see eq. (1)). The hypothetical earth ejecta must have been molten in order to account for the two periods of heating of the australites. Consequently, in order to explain the survival of nearly spherical drops of several centimeters radius, the atmosphere through which the molten primary bodies passed must have been much more tenuous than the 0.001 atmosphere required to enable rigid nonablating objects of these dimensions to escape the atmosphere.

The aerodynamic requirement developed earlier, that $p_s - p_b = \rho_\infty V_\infty^2 < 200$ dynes/cm^2 during formation of the primary australites, enables an upper limit to be established on the atmospheric density that is compatible with the hypothesis of australite origin from a terrestrial impact. The exit flight velocity would have to be essentially constant since the fused blobs could not withstand more than about 0.015 g deceleration; moreover, this nearly constant exit velocity from the atmosphere would equal the reentry velocity into the atmosphere, and this must be the order of 10 km/sec (see fig. 22). For V_∞ = 10 km/sec the aerodynamic requirement that $\rho_\infty V_\infty^2 < 200$ dynes/cm^2, becomes $\rho_\infty < 2\times10^{-7}$ atmospheres. This relatively high vacuum would have to be produced over a radius of about 500 kilometers to allow fused earth in the case of the australites to exit at angles as small as 12^o (see fig. 22, and note that the exit angle equals the entry angle). Such a vacuum over such an area would enable molten blobs of fused earth to fly through unmolested by aerodynamic forces. Thus far, however, it has not been explained how such an extensive vacuum might be produced from an impact: the monstrous aerodynamic obstacle to the hypervelocity flight of molten drops through the earth's atmosphere, has either been disregarded by the advocates of a terrestrial impact origin for tektites, or, if acknowledged, has been dismissed by invoking the saving assumption that somehow the atmosphere was removed.

When a large cosmic body enters the atmosphere, a region of relative rarefaction is, in fact, produced in its wake. Calculations from inviscid flow equations indicate that at high velocities a perfect vacuum can be produced; but, due to the effects of viscosity, the measured base pressure does not fall below about 0.1 of the ambient pressure (Chapman, 1951). Such a low-pressure region, that extends only for about one or two diameters downstream of the entering body and is there followed by the trailing shock wave, does not provide an "out" for the fused material.

When a blast wave from an intense explosion propagates through the atmosphere, a central rarefaction zone also is produced; and calculations from inviscid flow equations again indicate that a perfect vacuum can be produced at the center (Sedov, 1959). A crucial point, however, is that the propagation velocity of an intense blast wave attenuates rapidly with distance from the point of explosion: mass is conserved; the atmosphere is displaced radially outward from the blast center, rather than removed; and the hypothetical fused earth must eventually pass through and overtake the propagating wave of variable density and diminishing velocity. Numerical calculations using the approximate empirical scaling law of crater volume proportional to expended energy, and the equations of radially symmetric blast wave propagation (Sedov, 1959), show for example, that an object moving at 10 km/sec would soon overtake the propagating blast wave: after propagating a distance equal to the diameter of the crater produced by the impact, the wave propagation velocity would be small compared to 10 km/sec. Thus the blobs of hypothetical fused earth must fly at essentially constant velocity, first through the propagating field of continually increasing density within the blast wave, and then through the remaining portion of the earth's atmosphere exterior to the wave. In such a hypervelocity flight, the fused blobs would pass through densities far greater than the 2×10^{-7} atm limitation, and encounter relative breezes far stronger than that which molten drops of australite size can withstand without distortion or disruption. From our experiments we have seen that the requisite breeze for disrupting such drops is no greater than that which can be blown from a man's mouth, and this experimental result, together with the above considerations, leads us to reject the hypothesis of australite origin from an impact on earth, as well as from an impact on Venus, Mars, or any other planet which is shrouded with a substantial atmosphere.

A comparison of the entry trajectories which would be required for a terrestrial origin, with those determined for the australites is presented in figure 23. The dynamic restrictions for a terrestrial origin of these perfect buttons from the single site of Port Campbell are that $V_i < 11.2$ km/sec (the earth's escape velocity), and that the various V_i and γ_i values correspond to a fixed range from the supposed point of exit from the atmosphere. Lines of constant range, expressed in terms of the corresponding arc angle θ subtended at the earth's surface, are superimposed on the $V_i(\gamma_i)$ plot in figure 23. All possible entry trajectories compatible with a given range are represented by these lines. At range angles of less than about 90° (less than one-fourth the way around the globe) none of the corresponding $V_i(\gamma_i)$ points are within the domains of the various perfect buttons. For $\theta = 180°$, that is, an origin half way around the globe from Port Campbell, the ablation features of P.B. 1 could be accounted for, since the $\theta = 180°$ curve intersects the domain for this australite, but the ablation features on the others could not. For larger ranges, such as about 315°, or 7/8 the way around the globe, P.B. 4 or P.B. 6 could be accounted for, but not P.B. 1. It is clear, in fact, that there is no point of origin on earth which would be compatible with all of these trajectories determined for the perfect-button australites.

One technical point which warrants comment, concerns the influence on ablation calculations of the tektite temperature prior to entry into the atmosphere. Under the hypotheses of a terrestrial origin it might be expected that the tektites were still warm when they reentered the atmosphere. The temperature of ablation is so much higher than ambient temperature, however, that it makes little difference to the ablation process whether the initial tektite temperature was 300° K, for example, or a few hundred degrees higher. Even the largest australite cores are undeformed by the aerodynamic pressures to which they were subjected and, hence, were rigid prior to entry. Since these larger forms must have cooled to a temperature well below that for softening, the smaller buttons analyzed herein -- which would cool much more rapidly than the large cores -- would have been cool enough prior to entry that a knowledge of their exact initial temperature is not of major importance to the determination of their entry trajectories.

According to the foregoing evaluation of the two aerodynamics requirements developed in this paper -- namely, that the primary australites not be exposed during formation to more than a gentle breeze of air ($p_s - p_b < 200$ dynes/cm^2), and that the australite entry trajectories be compatible with those determined from their ablation characteristic -- neither is satisfied by the hypothesis of tektite origin from terrestrial impact. It is emphasized that the entry-trajectory evidence stands unaffected by the particular hypothesis as to how terrestrial debris might manage to emerge from the atmosphere: the atmosphere entry evidence would be equally applicable had the impact been from a large meteorite or a comet, or had the primary australites been otherwise propelled through the earth's atmosphere. Aerodynamic evidence of such a nature constitutes a valid basis for rejecting the hypothesis of terrestrial origin for the australites, and by inference, also for the other related groups of tektites.

Origin as ablation drops from a parent body.- This hypothesis was suggested in a primitive form by Hardcastle (1926), supported by Lacroix (1932) and Fenner (1938), revived in a modified form by O'Keefe (1960), and resupported by E. Adams and Huffaker (1962b). In the modified form, it is assumed that a large parent body grazed an edge of the earth's atmosphere at about parabolic velocity (11.2 km/sec) and shed numerous ablation drops; some of these drops are presumed to have exited from the atmosphere with a velocity somewhat less than the escape velocity, then solidified in their orbit around the earth, and finally reentered the atmosphere over Australia. Such a hypothesis relies on the rare incidence (a probability of several in a thousand) of a grazing rather than a direct entry. This hypothesis requires: (1) that the ablation occurred at a sufficiently high altitude so that drops of australite size were neither flattened nor disrupted by aerodynamic pressures; (2) that the reentry angle, which equals the atmosphere exit angle, was very shallow, no more than about $\sin \gamma_i = 0.1$ (6° from horizontal); and (3) that the tektites found at a fixed site come from essentially the same orbit and enter the atmosphere at essentially the same V_i, as well as at the same γ_i. That (1) is contradicted by the aerodynamic evidence may be seen as follows: the condition of equation (1) that $\rho_\infty V_\infty^2 < 200$ dynes/cm^2 during formation of the soft primary spheroids, at a grazing velocity of 10 km/sec, demands that

$1/2\ \rho_\infty V_\infty{}^3$ -- the maximum possible amount of aerodynamic heating per unit area from all convective and radiative sources -- be less than $1/2(200)(10^6)=10^8$ erg/cm^2 sec, or less than 2.4 cal/cm^2 sec. This is a relatively trivial amount of heating, insufficient to raise the parent body temperature above about 1100° K, and entirely inadequate to have brought about the ablation in the first place, thereby contradicting the ablation drop hypothesis. That (2) also is refuted by the aerodynamic evidence may be seen from the domain for no ring waves demarcated in figure 20. At the shallow entry angles required by the hypothesis of a grazing parent body, and for objects of typical australite size (R_B = 1 cm), p_{sf} is in the range from 0.02 to 0.05 atmospheres where no ring waves form. Thus this hypothesis is incompatible with the observations that ring-wave flow ridges invariably are present on well-preserved australites of such size. Finally, that (3) is contradicted by the Port Campbell australite entry trajectories may be seen from a glance at figure 22, which shows a wide range of entry conditions for $V_i(\gamma_i)$ rather than a single set. The parent body ablation drop hypothesis, therefore, is not considered further.

Extraterrestrial origin in general.- For a single shower of objects from an extraterrestrial source to have landed on only a small portion of the earth's surface, it would have been necessary for their entry velocities to all have essentially a common value, and for this value to have been greater than or approximately equal to, the earth's escape velocity of 11.2 km/sec. The various entry angles, however, need not have been the same even for tektites found at one site, provided the cluster is sufficiently large for the earth to have turned a substantial amount during the interval in which the cluster landed. Wide variations in entry angle for common-site tektites, however, imply large cluster dimensions, as is illustrated by some examples in figure 24. In this plot the domains covered by the various perfect buttons can be used, along with the equations for hyperbolic orbits, to compute the approximate cluster dimension corresponding to a given cosmic entry velocity. For example, for different common-site tektites to have entered at different angles within the range demanded by the various perfect button australites for V_i = 13 km/sec, the earth would have had to rotate for about 5 hours while the cluster landed; at the earth approach velocity of 6 km/sec, corresponding to V_i = 13 km/sec, this duration of landing implies a cluster of dimensions the order of 100,000 km. This is much larger than reasonably would be expected to land only on a confined portion of the globe. At lower values of V_i the implied cluster dimensions become smaller, approaching zero slowly at V_i approaches 11.2 km/sec. The implied cluster dimensions are a few thousand kilometers - the appropriate dimensions for the Australian continent - for values of V_i a fraction of a km/sec above the earth's escape velocity. This narrow range of entry velocity is the same as that originally deduced for the australites (Chapman, 1960).

Extrasolar-system origin.- Such an origin was suggested in 1898 by Krause (as reported by Baker 1959) and recently revived by Kohman (1958). For a cluster of objects to come from outside the solar system, the minimum possible velocity of entry into the earth's atmosphere would be about 16.6 km/sec. This minimum corresponds to an extremely rare circumstance, since it represents a trajectory which accidentally happens to approach in the plane of the earth's ecliptic, and which also happens to zero in along the same direction of motion as that which the earth has at the instant of entry. Even this extremely unlikely minimum condition, however, requires that the entry velocity be far greater than that which is compatible with the relatively small amount of ablation on australites, such as P.B. 1

or C625. The hypothesis of tektite origin from a source external to the solar system is unequivocally rejected by the aerodynamic evidence. It also has been rejected by Anders (1960) and by Viste and Anders (1962) on the equally substantial basis of an absence of the cosmic ray spallation isotope Al^{26} in tektites; such an isotope would be present in readily detectable amounts if the tektites had been long exposed to the interstellar cosmic radiation.

Origin from asteroidal belt, or lost planets.- The hypothesis of origin from disrupted planets, as suggested by Stair (1954) and Cassidy (1956), or from celestial objects in the solar system which are small enough to not possess an atmosphere, is compatible with the aerodynamic requirement that a negligible pressure differential for $p_s - p_b$ existed during primary formation; but such a hypothesis encounters contradictions with other evidence. The absence of detectable Al^{26} in tektites, for example, corresponds to a maximum cosmic flight time of 90,000 years (Viste and Anders). This maximum is several orders of magnitude smaller than the expected time of flight between the hypothetical production somewhere in the solar system and the accidental collision with the earth. Moreover, a typical meteorite from the asteroidal belt enters the earth's atmosphere at velocities of about 17 km/sec according to Whipple and Hughes (1955); and, as we have seen, these relatively high entry velocities are incompatible with the ablation evidence. Even extremely rare trajectories from the asteroidal belt which happen to enter in the plane of the ecliptic and along a path tangent to that of the earth at the instant of collision, require velocities of about 13 km/sec, and these imply excessive cluster dimensions. Additional contradictory evidence has been pointed out by Urey (1955, 1957) from considerations of the magnitude of cluster density which, during heliocentric orbit of a tektite swarm, is required to prevent dispersion through the perturbing differential attractions of the sun's gravitational field. The requisite cluster density during orbit at the earth's distance R from the sun of mass M is about M/R^3 (see, e.g., Russell, Dugan and Stewart, 1945, p. 446), and this amounts to about 10^{-6} gm/cm^3 which, for the Australian strewnfield of 3,000 km breadth, implies an area density of 300 gm/cm^2 -- or a layer of tektites piled about a meter deep. This definitely is not the case. As Urey has pointed out, these cogent considerations of requisite cluster density eliminate many hypotheses as to tektite origin, and leave only the earth, the earth's moon, and an extrasolar origin for consideration. We have already rejected the earth and an extrasolar origin from aerodynamic evidence, and, thus, by the process of elimination, are left with the moon as the expected source of origin.

Lunar origin of tektites.- This hypothesis was suggested early by Verbeek (1897) who regarded the lunar volcanoes as possible sources of tektite origin. Linck (1928) has given this ideal some support, and Nininger (1943) has advanced the specific suggestion that a meteoritic impact on the moon was the mechanism which sent tektites to the earth. The evidence for lunar origin of the australites is much more substantial than the evidence outlined above from the negative approach of discrediting or eliminating essentially all other origins. Gault, Shoemaker, and Moore on the basis of recent hypervelocity impact experiments at the NASA Ames Research Center show that impact at $V \approx 6$ km/sec is sufficient to fuse quartz particles. Since meteorites strike the moon at considerably greater velocity, and apparently produce some very large craters, a mechanism is provided for sending a quantity of fused lunar crust to the earth which is ample to account for the mass of tektites. In this regard it is to be noted that the amount of fusion increases as the compressibility of the target material increases. One of the most consistent results from optical and radio wave observations of the moon (e.g., Baldwin, 1961, Giraud, 1962, Troitski, 1962) is that the lunar crust is composed of a vesicular, hence, compressible, material. The deduction of Troitski, for example, that $\rho = 0.5\ gm/cm^3$ corresponds to a lunar crust that is composed of a frothy material that is mainly voids and that is readily fused upon being shock compressed from an impact. It is pertinent to note also that the presence of threadlike rays emanating from certain of the lunar craters is proof that a mechanism exists for directing crater debris to within a sufficiently confined angular dispersion so as not to cover the entire earth, but to over-spread areas of continental dimensions. Moreover, this "jetting" phenomenon is commonly observed in hypervelocity impact experiments (Denardo, 1962).

The most decisive evidence for associating tektites with the moon comes from the aerodynamic considerations. The requirement that $p_s - p_b = \rho_\infty V_\infty^2 < 200$ dynes/cm^2 during primary tektite formation is obviously satisfied by the moon's extremely tenuous atmosphere; and the aerodynamic requirement from the trajectory determinations, that the entry velocity be in the range slightly above about 11.2 km/sec - as deduced for the Port Campbell buttons whose entry trajectories are represented in figure 24 - is uniquely compatible with a lunar origin. In this way the aerodynamic evidence directly connects the australites, and hence the other related tektites, with the moon.

No conclusion based on deductions from experimental investigations is absolute in the sense that it does not rest on some assumption. In the present case the trajectory evidence, which appears to reject unequivocally all celestial objects except the moon, is based on the fundamental assumption that the primary australites were either spheres or nearly spherical spheroids prior to entry into the atmosphere. We have shown how this can be proven to have been the case for certain australites. To our knowledge this cannot be proved for all of them. This particular assumption, however, is based on the results of studies of thousands of australites by Fenner and Baker, and thus far has not been questioned in the tektite literature. The present trajectory evidence for the australites is also based on the assumption that most of the primary spheroids were either not rotating prior to entry, or, if rotating, were turning with a sufficiently slow motion to be damped before ablation started, so that the ablative phase of entry occurred in the absence of significant yawing or pitching motions. It is to be noted that many of the perfect buttons analyzed possess a ring-wave system that is remarkably concentric, and could not have had any appreciable transverse motion during ablation. This evidence, together with that previously discussed as to the general absence of surface melting on the bubble-pitted posterior surfaces, lead us to disregard consideration of slow initial turning in analyzing the majority of perfect button australites. For an occasional one which, prior to entry, may have been turning about an axis perpendicular to the flight path, the actual entry velocity would be somewhat higher than computed herein. On the other hand, for a primary spheroid that was sizably oblate, rather than closely spherical, the actual entry velocity would be lower than computed. The over-all entry conditions deduced for the three groups of perfect buttons represent the majority of perfect buttons, and are believed not to be significantly affected by these considerations.

One of the most interesting aspects about the idea of a lunar origin for tektites is the consequence therefrom that the moon, like the earth, is a thoroughly differentiated celestial body. The moon is not sufficiently massive to encompass within its interior significant variations in density due to compressibility of the solid matter of which it is composed. Since the density of tektites (2.3-2.5) is considerably less than that of the moon's average (3.3), it follows that the interior cannot be homogeneous, and that the crust must be lighter than the core. Under the accretional hypothesis for formation of bodies within the solar system from common cosmic matter, a differentiation in density of this magnitude would be associated with a differentiation in chemistry, and major differences would be expected in the distribution of chemical elements between tektites and the cosmic, or solar, average. To provide a background for comparison of various chemical abundances, we have represented in figure 25 the logarithm of the elemental abundances in the sun, the meteorites, the early-type hot B-stars, and the planetary nebulae. These distributions, which are normalized relative to log N = 5 for Si, were compiled from the literature (Aller, 1959; Goldberg, Muller, and Aller, 1960; Krinov, 1960; Suess and Urey, 1956). Where discrepancies existed for a given element, an average was taken. As is well known, the sun, and certain of the stars and nebulae, exhibit mutually similar abundances, with the light-gas elements H and He being the most prevalent. The meteorites, on the other hand, come from relatively small accumulations of matter and are highly deficient in the volatiles relative to their massive and luminous cosmic relatives. For the nonvolatile elements, however, the various celestial objects exhibit a remarkable uniformity. One exception is Li, which is low in the sun; but this circumstance is explicable in view of the consumption of Li through solar nuclear reactions. Consequently, a mean cosmic distribution of elements can be obtained from these data, and such a distribution is identified as "solarcosmic" in figure 26 wherein it is compared with the average elemental distributions within the earth crust and within tektites. Data for the elemental abundances in the earth crust were taken from Mason (1958) and Rankama (1954), and that for tektites from Buddhue (1956) and subsequent papers (Krinov, 1958, Taylor and Sachs, 1960). As would be expected, both the earth crust and the tektites are highly deficient in the volatile elements; more important, when a given nonvolatile element departs substantially from the solar-cosmic abundance, it does so for both earth crust and tektites. The relatively high K, U, and Th abundances, and the relatively low Cr, Ni, and Co abundances, are characteristic of chemically differentiated matter. Thus a lunar origin for tektites leads to some important consequences about the chemical make-up of lunar crust and about the cosmological history of the moon: the average elemental abundances of lunar crust are not grossly different from earth crust; and sometime in its past the moon has been sufficiently heated, presumably by radioactive elements, to have become a chemically differentiated body.

CONCLUDING REMARKS

We have confined our attention almost entirely to the australites, from necessity rather than choice. Few of the other tektites exhibit features of surface sculpture or profile form that demonstrably are aerodynamic in origin. The absence today of aerodynamic markings on such ancient tektites as those found in North America (over 30-million years K-A age) and in Czechoslovakia (about 14-million years K-A age) is readily understandable and demands little comment.

But, to the authors' knowledge only a partial or clouded aerodynamic record is present on the much younger tektites from Indochina, Indonesia, and the Philippines, which have the same K-A age as the australites. This circumstance warrants considerable comment and involves several important unanswered questions.

Perhaps the most fundamental question about the "australasian" tektites - that is, those strewn from Tasmania to South China, and from Thailand to the Philippines, - is whether or not they represent a single event. Evidence both suggests and questions the hypothesis that one grand shower of related groups of tektite clusters descended over these areas of the globe. Many striking chemical similarities between the various australasian tektites have been long known, and have been recently emphasized in the study of Pinson (1962). Von Keonigswald (1960, and his earlier papers referred to therein) has pointed out certain systematic morphological variations in the shapes spread from Australia to China, and has associated contemporaneously the tektites found in four different sites in Indonesia and the Philippines with the remains of fossil mammals of middle to upper Pleistocene Age. The potassium-argon dating of Gentner and Zahringer (1960) has indicated a common K-A age of 0.6×10^6 years for each of the various groups of australasian tektites. Also, the present experiments on the primary forms into which glass of various viscosity breaks up provides an explanation of how it is possible for the widely contrasting shape groups (e.g., dominantly teardrops in Indochina, yet dominantly spheres in Australia) to come from different portions of a single large mass of fused material; this parent material need only be nonuniform in temperature by a relatively small amount to produce the widely different shape groups. On the other hand, this picture of a unified australasian tektite fall is opposed by evidence from several other sources. Barnes (1961), for example, indicates his belief that the geological age of the javanites, indochinites, philippinites, and australites are all different; and Baker (1960) concludes from his extensive studies of the australites that they have not been around since Pleistocene times, but have been exposed no more than 5,000 years to atmosphere and terrestrial agents. It is clear that additional research is required to fully clarify the question of the ages and of the number of falls comprised by the australasian tektites.

Another important problem associated with the australasian tektites is that of explaining why aerodynamic sculpturing today is common on the australites, yet appears to be rare on the indochinites, philippinites, and javanites. Occasionally it is stated that only the australites show evident aerodynamic markings; but we have noted recently (Chapman, Larson, Anderson, 1962) that over a hundred of the smaller javanites in the collection of von Koenigswald exhibit clear aerodynamic sculpturing. More commonly, however, the javanites are fragments, termed "tektite waste" by von Koenigswald, and like many indochinites appear to be broken and corroded portions of what were once much larger specimens of unknown shape. In considering the apparent absence of aerodynamic markings on less regular shapes than the australites, such as on the tektites found in Asia, several important aerodynamic circumstances other than fragmentation are to be kept in mind. Three ways in which aerodynamic ablation can be revealed are by the presence of a flange, the existence of an obviously modified profile contour, and the existence of systematic striae distortions in a very thin layer beneath the tektite surface. Of these, the most conspicuous feature would be the presence of a flange; but melt flow can be expected to accumulate into a flange only if a tektite is capable of flight at a fixed orientation, and if the primary tektite is of sufficiently regular shape to possess about its circumference a continuous closed line of flow separation that remains essentially fixed relative to the body. Such is not to be expected on irregular shapes, nor on shapes such as teardrops that are expected to turn during entry. If a teardrop, for example, were slowly turning prior to entry, it would continue to turn during the ablative phase: A flange would not be formed; the heating would be spread all around the circumference and would be incapable of removing during a steep parabolic entry more than the order of a millimeter of glass from the original contour. After many thousands of years of exposure to tropical corrosion, such a tektite, which never possessed a flange nor exhibited a marked alteration in profile contour, also will not exhibit a thin outer layer of systematic stria distortions. Under these circumstances the aerodynamic record is first blurred and then erased; and the apparent absence today of australite-like sculpturing on the indochinites is not a valid premise for concluding that these tektites did not once possess a thin veil of aerodynamic markings on their exterior. This explanation is merely a possible one; it may not be the correct one, and it certainly is not the only one. For example, another possibility is that some very large masses of glass, the cores of which were still in a fluid but highly viscous state, were broken up by the large aerodynamic forces associated with large entry objects. In order for an object to still be hot after a journey from the moon, however, it would have to be of large dimensions, estimated to be the order of meters. Thus far there is little substantial evidence for such a hypothesis; while it offers an explanation of the myriads of teardrop forms found in Indochina (some of which are flattened), the high concentration of tektites found in certain areas of Southeast Asia, the dominance of apparently "unablated" tektites throughout these areas, and the presence of occasional large chunks of tektite glass, it may not withstand detailed petrological scrutiny. Such a possibility is mentioned here to emphasize our view that the true sculpturing processes are much less clear for the Asian, than for the Australian tektites, and that much more research is required to arrive at a satisfactory explanation.

The uncertainty of circumstances under which the Asian tektites were formed does not detract from the strength of the aerodynamic evidence as to the origin of the Australian tektites. On the external surface and within the internal structure of the australites, there has been implanted an aerodynamic record of manifest clarity: the presence of ring-wave flow ridges and coiled circumferential flanges, which are reproducible in the aerodynamic laboratory; the presence of rare shapes with wide, hatbrim flanges and a single ring wave, which shapes also are reproducible in the laboratory under correspondingly rare aerodynamic conditions; the existence of a certain geometric relationship between the front curvature and the depth of australites, which is the same relationship as that produced by aerodynamic ablation; the presence of curious zigzag striae patterns in portions of australite flanges, which are also present in the corresponding portion of flanges, produced by aerodynamic heating; the existence of a very thin layer -- as thin as the fusion crust on meteorites -- of systematically distorted glass striae, which are reproducible in the laboratory and are describable through precisely the same mathematical functions required by the theory of aerodynamic ablation; and the existence of a unique character of the external shapes of australites, almost all of which, when oriented in the particular manner demanded by the pattern of ring waves and flow lines on the front face, represent configurations of static and dynamic stability during a descending entry into the atmosphere. These circumstances leave no doubt that the australites have been sculptured by aerodynamic heating of rigid tektite glass during the process of a hypervelocity descending entry into the earth's atmosphere. The confirmation through numerous ablation experiments of the analytical methods for computing the characteristics of ablation of tektite glass provides a sound basis for determining the entry trajectories of these tektites; and the principal results of this paper -- that the australite entry trajectories are uniquely compatible with origin from the moon, and that the primary australites were formed in a near vacuum -- constitute a strong case indeed for the lunar origin of tektites.

Ames Research Center
National Aeronautics and Space Administration
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APPENDIX

ABLATION EQUATIONS AND PHYSICAL PROPERTIES OF TEKTITE GLASS

A complete description of the analytical methods used to compute the ablation characteristics of tektite glass would comprise the proportions of a separate paper. In this appendix, however, a condensed account is presented of the principal equations solved and of the most important physical properties of tektite glass.

The three basic conservation equations describing flow of the viscous layer of fluid glass in the vicinity of a stagnation point are well known. They are simpler than the full equations of viscous fluid motion inasmuch as inertia terms are negligible compared to shear and pressure gradient terms. In a curvilinear coordinate system of the boundary-layer type, with independent space variables (x, y) measured in the directions illustrated in figure 6, and with corresponding velocity variable (u, v) measured similarly, the conservation equations for the flowing glass layer are:

Momentum

$$\frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) = \frac{dp}{dx} - \rho a \frac{x}{R_F}$$

Mass

$$\frac{\partial u}{\partial x} + \frac{u}{x} + \frac{\partial v}{\partial y} = 0$$

Energy

$$\rho c_p \left(\frac{\partial T}{\partial t} + v \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial y}\left[K \frac{\partial T}{\partial y} + F(y, t)\right] = 0$$

Physical properties of the glass are represented by the density ρ, viscosity μ, specific heat c_p, and thermal conductivity k. Aerodynamic conditions determine the pressure gradient dp/dx and the body-force term $\rho ax/R_F$: in a laboratory experiment the "acceleration" a would equal $+g$ (gravitational acceleration) for an air stream moving vertically downward, $-g$ for one moving vertically upward, and zero for one moving horizontally; in an atmosphere entry a would equal the negative of the deceleration, and would be variable from point to point in the trajectory. The net flux of radiant energy transported in the y direction is (see Kourganoff, 1952; and Kadanoff, 1961)

$$\frac{F(y, t)}{2n^2\alpha\sigma} = \int_0^\infty T^4(\eta)E_2[\alpha|y - \eta|]\, d\eta + \left(1 - \frac{\epsilon_m}{n^2}\right)\int_0^\infty T^4(\eta)E_2[\alpha(y + \eta)]\, d\eta$$

where n is the index of refraction, α the absorption coefficient (cm^{-1}), σ the Stefan constant (1.369×10^{-12} cal/cm^2 sec $^{\circ}K^4$), and ϵ_m the maximum emissivity for uniform temperature (a function of n, as given by Gardon, 1961).

The equations for momentum and mass conservation are readily solved. In the vicinity of a stagnation point u varies linearly with x, and the momentum equation can be integrated to yield

$$\frac{\partial u}{\partial x} = \frac{u}{x} = \left(p'' - \frac{\rho a}{R_F}\right) \int_{\infty}^{y} \frac{y\, dy}{\mu} + \tau'_w \int_{\infty}^{y} \frac{dy}{\mu}$$

where τ'_w is the wall shear stress gradient $d\tau_w/dx$ at the glass-air interface. Similarly, with $\partial u/\partial x$ known, the mass equation can be integrated

$$v = -2 \int_{\infty}^{y} \frac{\partial u}{\partial x}\, dy + v_{\infty}$$

where v_{∞} is the ablation rate, or velocity of recession, of the stagnation point. Throughout this paper,

$$y_s = \int_{0}^{t} v_{\infty}\, dt$$

is used to designate the recession distance of the stagnation point.

One of the two mathematical procedures employed to solve the energy equation utilizes an integral method; designated Method I herein. Integral methods are commonly used in boundary-layer analyses, and lead to relatively simple computations through the artifice of converting the partial differential equation for $T(y, t)$ into an ordinary differential equation. Details of the procedure are not given here, as they are similar to those of previous investigations (e.g., Bethe and M. Adams, 1959, Georgiev, 1959). It will suffice to note that the particular method employed represents a generalization of the previous methods to include the effects of internal radiations, of a temporally varying emissivity, of body forces, and of a certain small term in the energy equation which was disregarded in the original paper of Bethe and Adams. In Method I the momentum and mass equations are solved analytically by representing the temperature distribution within the thin liquid layer as an exponential function. For a given aerodynamic input (given heating rate $q_o(t)$, enthalpy $h_s(t)$, pressure $p_s(t)$), the machine program computes the extent of ablation y_s (cm), the amount of vaporization v_w/v_{∞}, the surface temperature T_w ($^{\circ}K$), the characteristic thickness of liquid layer δ (cm), and several other quantities as a function of time. In order to obtain close agreement with experiment, M. Adams, Powers, and Georgiev (1960) have shown that even for "opaque" glasses the liquid layer must be treated as fully transparent. The underlying reason for this is attributed to the extremely high rates of aerodynamic heating; they produce such thin liquid layers ($\delta \approx 0.003$ to 0.005 cm during peak heating of australites) that only a small fraction of the exiting radiant energy is absorbed within this thin layer. Calculations for truly opaque glass yield ablation rates that are higher than experiment.

The second mathematical procedure employed to solve the energy equation (designated Method II) utilizes the technique of finite difference calculation. We are indebted to our colleague, Mr. Fred W. Matting, who assisted with this method of computation. Details of the finite difference procedure, as applied to ablation of glasses and other materials, may be found in several papers (Landou, 1950; Lotkin, 1960; Fledderman and Hurwicz, 1960: and E. Adams, 1961). It will suffice to note here that a forward difference procedure was used in the present computations, as in these previous investigations. This strictly numerical procedure solves each of the three basic conservation equations by taking small step-by-step increments in time. The requisite smallness of time increment is determined empirically by the process of employing successively smaller increments until no appreciable changes in end results are obtained. The machine program for Method II computes the same quantities as for Method I, but requires an order of magnitude more machine computation time. Both methods provide good results, as shown elsewhere in this paper.

Various aerodynamic equations common to Methods I and II are employed in the computations. The principal equations involve the aerodynamic heating rate for zero vaporization q_o, the heat blockage factor ψ due to vaporization, the mass rate of vaporization, the mass rate of vaporization ρv_w, the pressure p_v and heat h_v of vaporization, the glass thermal conductivity k_w and air enthalpy h_w at the wall temperature, the stagnation-point enthalpy h_s and pressure p_s, the velocity gradient du_e/dx at the external edge of the boundary layer, and the shear stress at the wall with vaporization τ_w and without τ_{w_o}. These equations are listed here for reference.

Wall boundary condition:

$$\psi q_o = \rho v_w h_v - k_w \left(\frac{dT}{dy}\right)_w$$

Solution to boundary-layer diffusion equation (for Lewis number Le and ratio M of vapor to air molecular weight):

$$\frac{\rho v_w (h_s - h_w)}{q_o} = \frac{\psi(Le/M)}{\left[(p_s/p_v) - 1\right]}$$

Heat blockage factor as determined from various solutions to the boundary-layer equations:

$$\psi = \frac{0.94}{1 + \dfrac{a_1}{\dfrac{p_s}{p_v} - 1}} + 0.06$$

Shear reduction factor similarly determined:

$$\frac{\tau_w}{\tau_{w_o}} = \psi \left(1 + \frac{a_2 \psi}{\frac{p_s}{p_v} - 1} \right)$$

Relationship between shear and heat transfer for no vaporization

$$\frac{\tau'_o (h_s - h_w)}{q_o \left(\frac{du_e}{dx} \right)} = a_3$$

Vaporization suppression by oxygen:

$$\frac{p_s}{p_v} = \left(\frac{p_s}{p_{v_*}} \right)^m$$

Velocity gradient:

$$\frac{du_e}{dx} = \frac{V_\infty}{R_F} \frac{\sqrt{2\rho_\infty / \rho_s}}{f}$$

In this last equation ρ_∞/ρ_s is the ratio of air density upstream of the shock to that at the stagnation point, and f is a factor close to unity which is determined from experiment in a given arc jet, and, from solutions to the inviscid external flow equations in hypervelocity flight.

The three aerodynamic constants appearing in the above equations are determined from various numerical solutions to the boundary layer equations: the value employed herein for tektite glass are $a_1 = 0.95$, $a_2 = 0.28$, and $a_3 = 1.025$. The exponent $m = 1.4$ is deduced from the chemical reaction equations for vaporizing silica (e.g., Hidalgo, 1960).

The above equations are applicable to the continuum gas dynamic regime. During an entry flight the free molecule regime and then a transitional regime are encountered before the continuum regime. In the free molecule flow regime there is no heat blocking effect by the vaporizing species. The essential equations in this regime are well known (Hayes and Probstein, 1959) and need not be reproduced here. Equations for the transitional regime are less well known, the most important of which is that for the aerodynamic heating rate. It has been found, from the experiments of Ferri and Zakkay (1962), that a good analytical representation of the experimental data is

$$q_o = \frac{q_{o_{FM}} q_{o_c}}{\sqrt{\left(q_{o_{FM}}\right)^2 + \left(q_{o_c}\right)^2}}$$

where q_{o_c} is the continuum value, $q_{o_{FM}}$ the free-molecule flow value, at any given Reynolds number. Analogous transition equations have been developed and used in the computation of tektite trajectories for the other aerodynamic quantities which enter the analysis.

The most important equation of the entire analysis is that for the rate of heating at a stagnation point in laminar continuum flow. With R_F in cm, flight velocity V_∞ in km/sec, air density ρ_∞ in gm/cm³ and q_{o_c} in cal/cm² sec, we have

$$q_{o_c} = \frac{1110 \sqrt{\rho_\infty}\, V_\infty^{3.15}}{\sqrt{R_F}} \left(1 - \frac{h_w}{h_s}\right)$$

This equation is established on both analytical solutions of the full boundary-layer equations (Fay and Riddell, 1957) and on experimental correlations or shock-tube experiments (Detra, Kemp, and Riddell, 1957); in addition, it has been confirmed in flight tests (e.g., Yee, Bailey, and Woodward, 1961). Other equations, such as those pertaining to gas cap radiation, and to the effects on q_{o_c} of vorticity interaction and ionization, are of relatively small importance in the entry conditions of australites and are not discussed here. Such factors, though, have been considered in all of the computations.

The above equation for q_{o_c} applies only to a body that either is not turning or is turning about an axis parallel to that of the flight path. As previously noted a small portion of the australites may have been turning slowly prior to entry into the earth's atmosphere; but, the existence of a slow, pre-entry turning of a sphere which would not be opposed by aerodynamic damping forces other than rotational friction until ablation begins, would not necessarily be discernible from a study of the final ablated sculpture. This situation arises because the aerodynamic forces are strongly stabilized as soon as the ablation y_s progresses to a degree, say, $y_s/R_F \approx 0.2$ for which the ablated shape becomes highly stable. If the turning axis happens to be perpendicular to the flight path, any portion of the surface is exposed during pre-ablation heating to a rate that is, at most, one-fourth that of the stagnation-point heating rate. During the initial stages of ablation, as the wobbling tektite settles into a stable position, the wandering stagnation point exposes the surface to heating rates that finally approach the full value q_o for stable flight. The heating rate expression

$$q = \left\{0.25 + 0.75\left[1 - e^{\left(\frac{y_s}{0.2R}\right)^2}\right]\right\} q_o$$

has been used in the present calculations to allow for the influence of pre-entry turning on the amount of ablation that occurs during entry.

During the atmosphere entry of a tektite, the radius of curvature R_F, the mass m, the drag coefficient C_D, and the frontal area A all vary with the extent of ablation y_s. The appropriate $R_F(y_s)$ function for the australites, as illustrated in figure 3, has been used in the entry trajectory computations. Similarly appropriate functions representing the variation in m, C_D, and A also have been developed and used in the computations.

Indispensable to all the calculations is an adequate knowledge of the various physical properties which affect ablation. As mentioned earlier, some of the physical properties of tektite glass depend in an important way on the chemical composition, especially the silica content. Inasmuch as a full account of measurements conducted to date on these properties would swell this paragraph into a brief paper, only a typical set of these data, namely, that for the average Port Campbell australite containing 76-percent silica is listed here (T is in $^{\circ}K$):

Density (chemical balance measurement):

$$\rho = 2.40 \text{ gm/cm}^3$$

Specific heat (from calorimeter measurement):

$$c_p = 0.228 + 0.00006T - \frac{6500}{T^2} \frac{\text{cal}}{\text{gm } ^{\circ}\text{K}}$$

Thermal conductivity (from c_p, ρ, and thermal diffusivity measurement by a sandwich method):

$$k = 0.00405 - \frac{0.45}{T}$$

Viscosity (from rotating cylinder measurement):

$$\ln \mu = \frac{27620}{T - 262} - 9.09 \qquad \text{poise}$$

Vapor pressure (mass loss measurements):

$$\ln p_{v_*} = - \frac{57800}{T} + 19.1 \qquad (p_{v_*} \text{ in atm})$$

Heat of vaporization (same as silica):

$$h_v = 3050 \text{ cal/gm}$$

Opacity (appropriate wave length integration of data of Cohen (1958)):

$$\alpha = 19 \text{ cm}^{-1}$$

Index of refraction (Barnes 1939, Baker, 1959):

$$n = 1.50$$

Maximum emissivities (Gordon, 1961, for above value of n):

$$\epsilon_m = 0.91$$

It is emphasized that these are the properties for only one composition of Australian tektite glass. Some of the australites from the same location, namely, Port Campbell, correspond to $\rho = 2.37$, to lower p_V, and to higher μ; while others correspond to $\rho = 2.44$, to higher p_V, and to lower μ. The appropriate variation in properties has been used for all computations presented herein.

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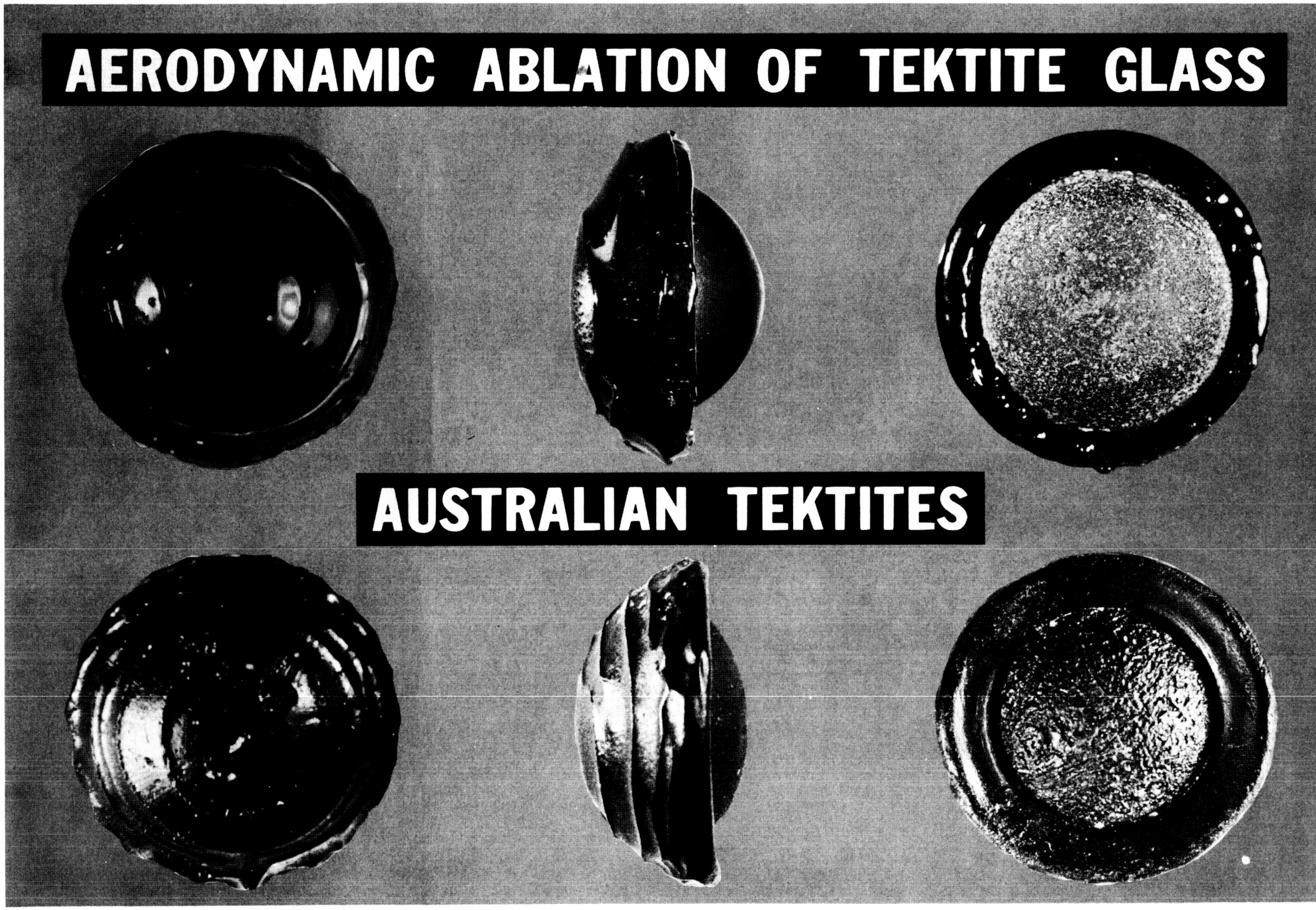

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Figure 1.- Comparison of three Australian button tektites (now in British Museum) with three tektite glass models ablated by aerodynamic heating.

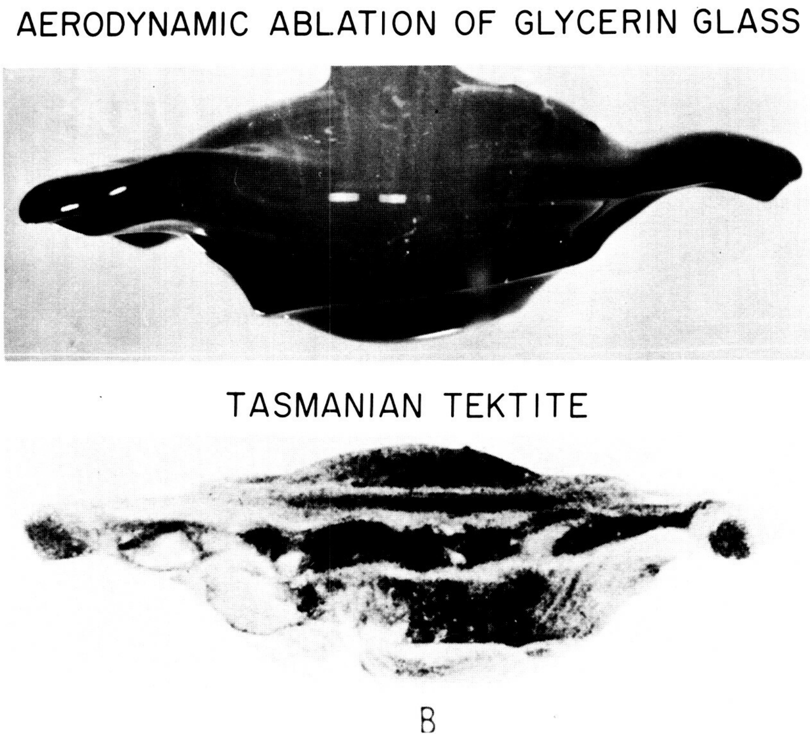

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Figure 2.- Comparison of a wide-flange tektite from Tasmania with a model of glycerin glass photographed during ablation in a vertical wind tunnel.

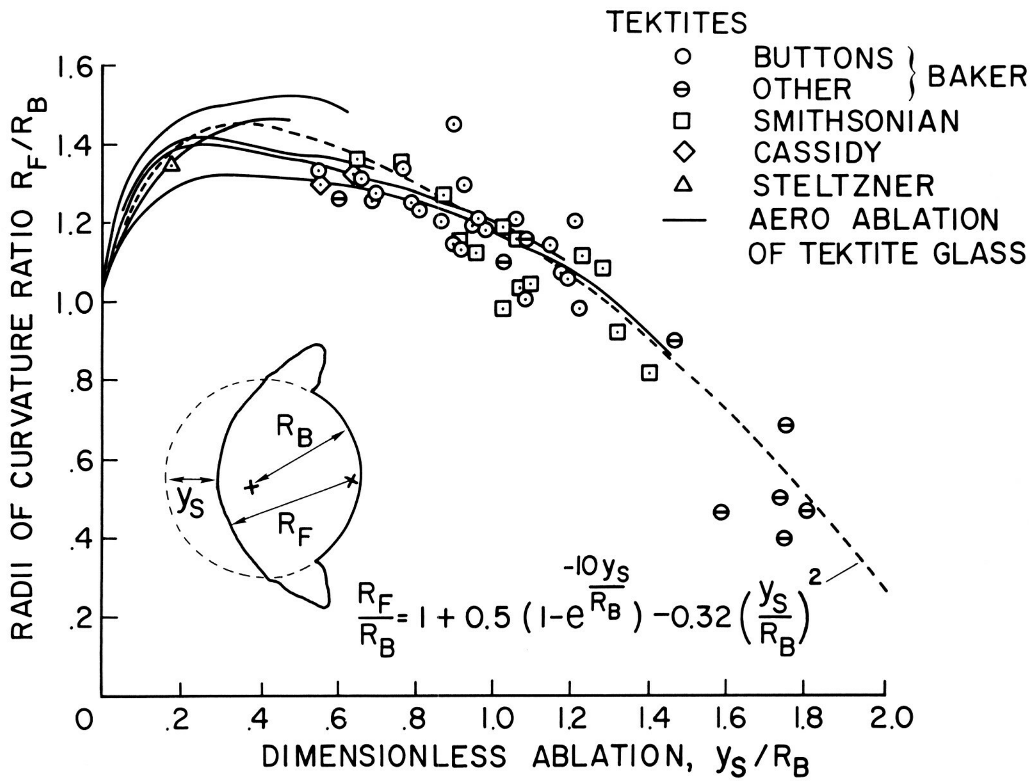
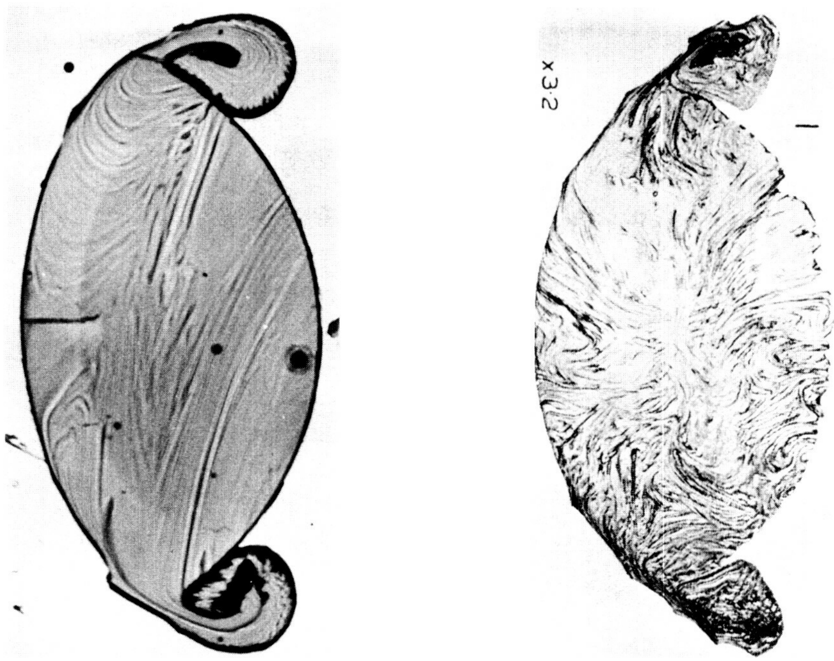


Figure 3.- Congruence between geometric relationships of Australian tektites and tektite glass models ablated by aerodynamic heating.

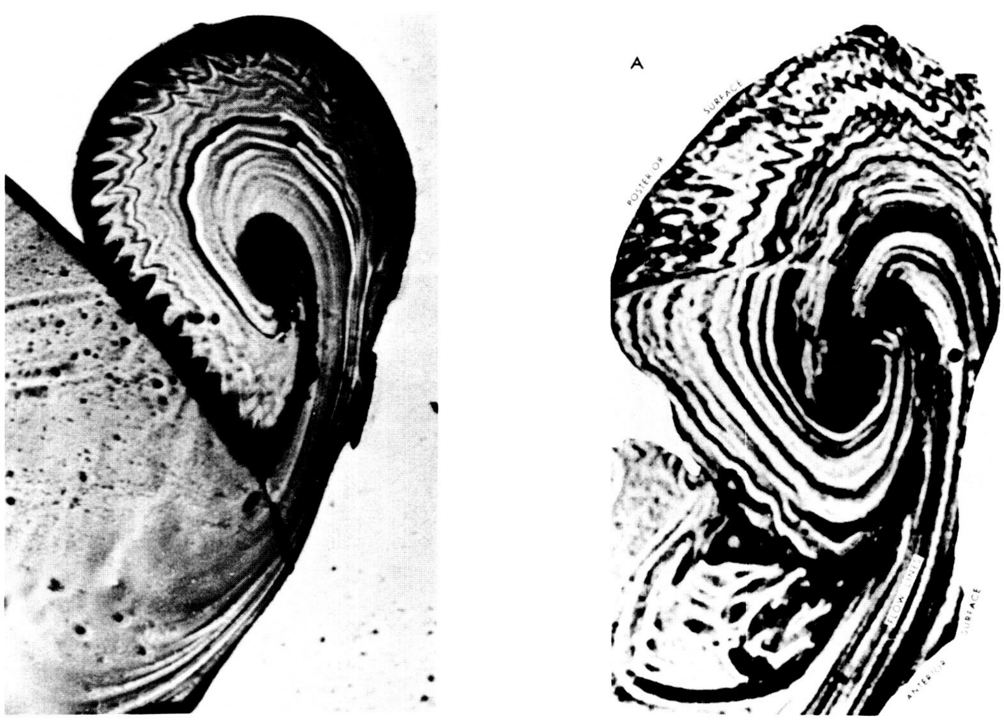


AERODYNAMIC ABLATION OF TEKTITE GLASS

AUSTRALIAN TEKTITE

A-29583-4

Figure 4.- Comparison of thin section of an australite (Baker 279, Port Campbell, Victoria) with thin section of a model of tektite glass (constructed from a rizalite) ablated by aerodynamic heating.



AERODYNAMIC ABLATION OF TEKTITE GLASS

AUSTRALIAN TEKTITE

A-29583-5

Figure 5.- Correspondence of details of flange structure.

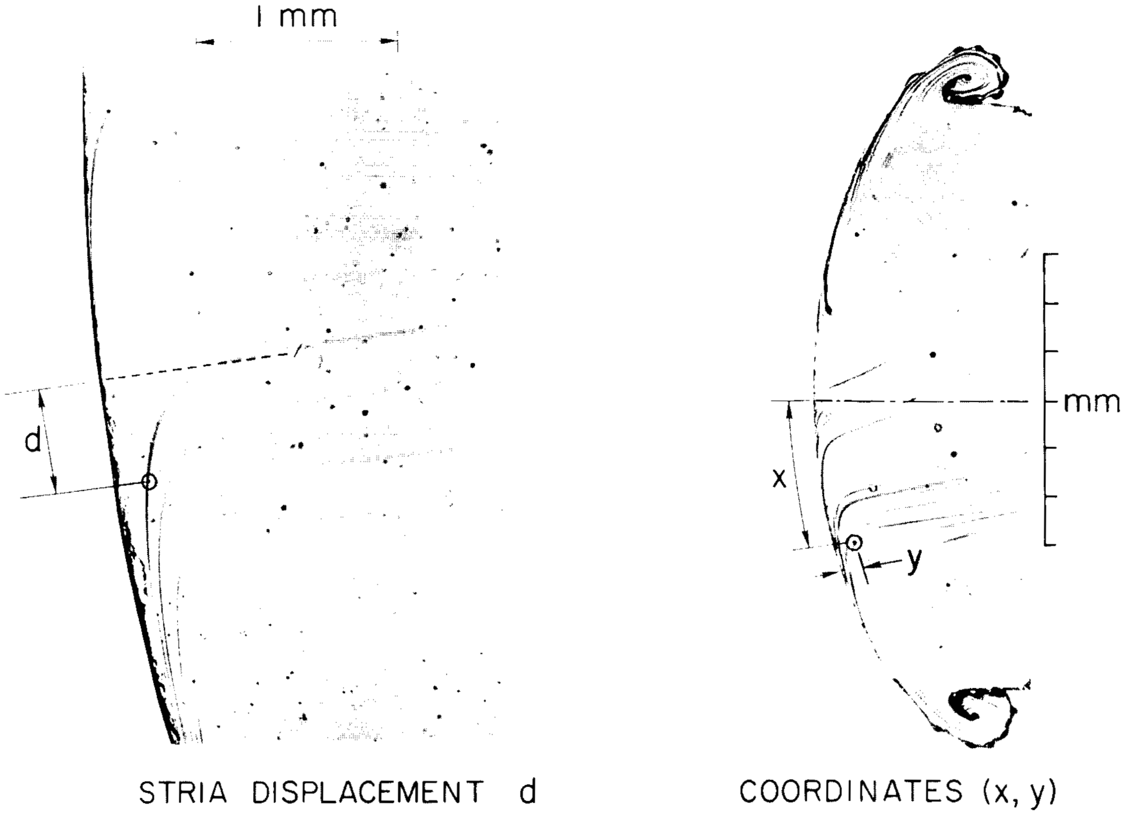


Figure 6.- Quantities defining striae displacement. A-29583-6

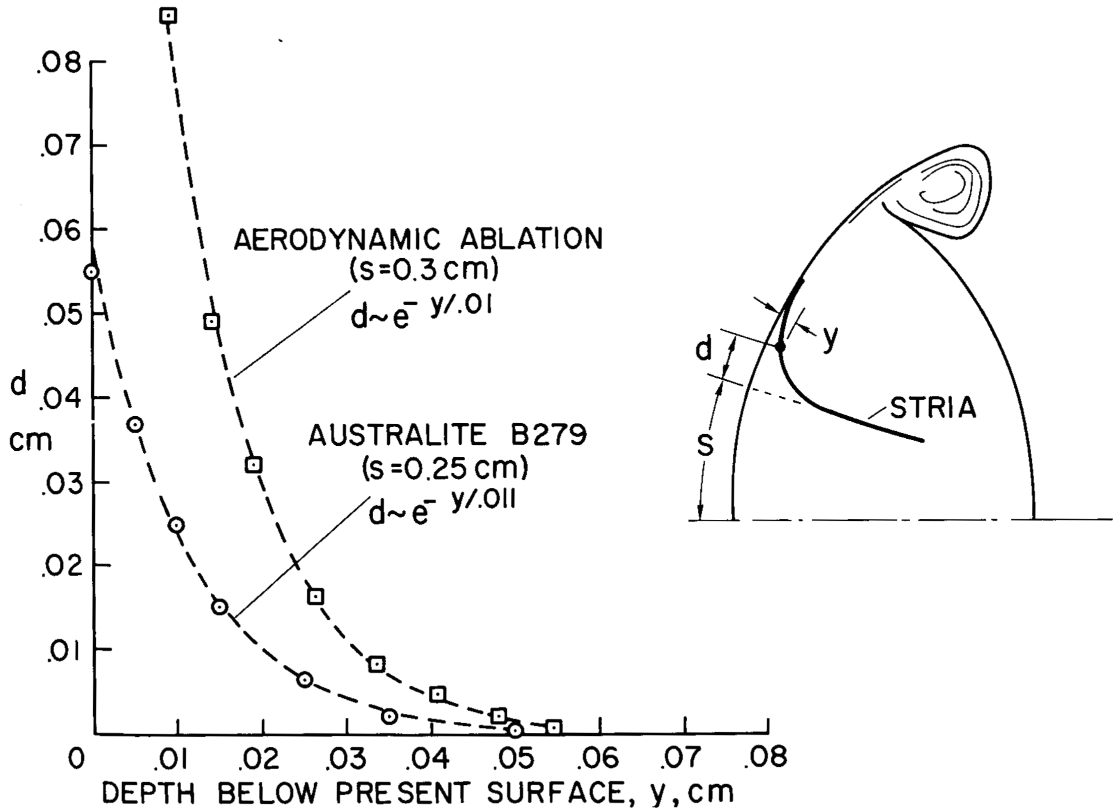


Figure 7.- Correspondence of d(y) striae displacements.

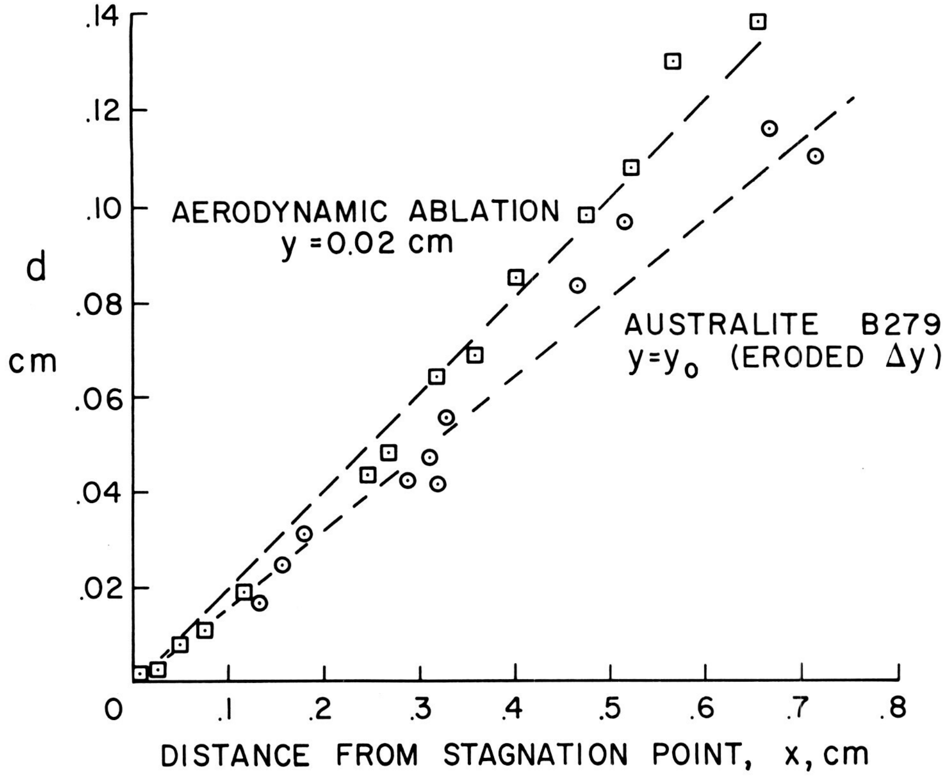


Figure 8.- Correspondence of d(x) striae displacement.

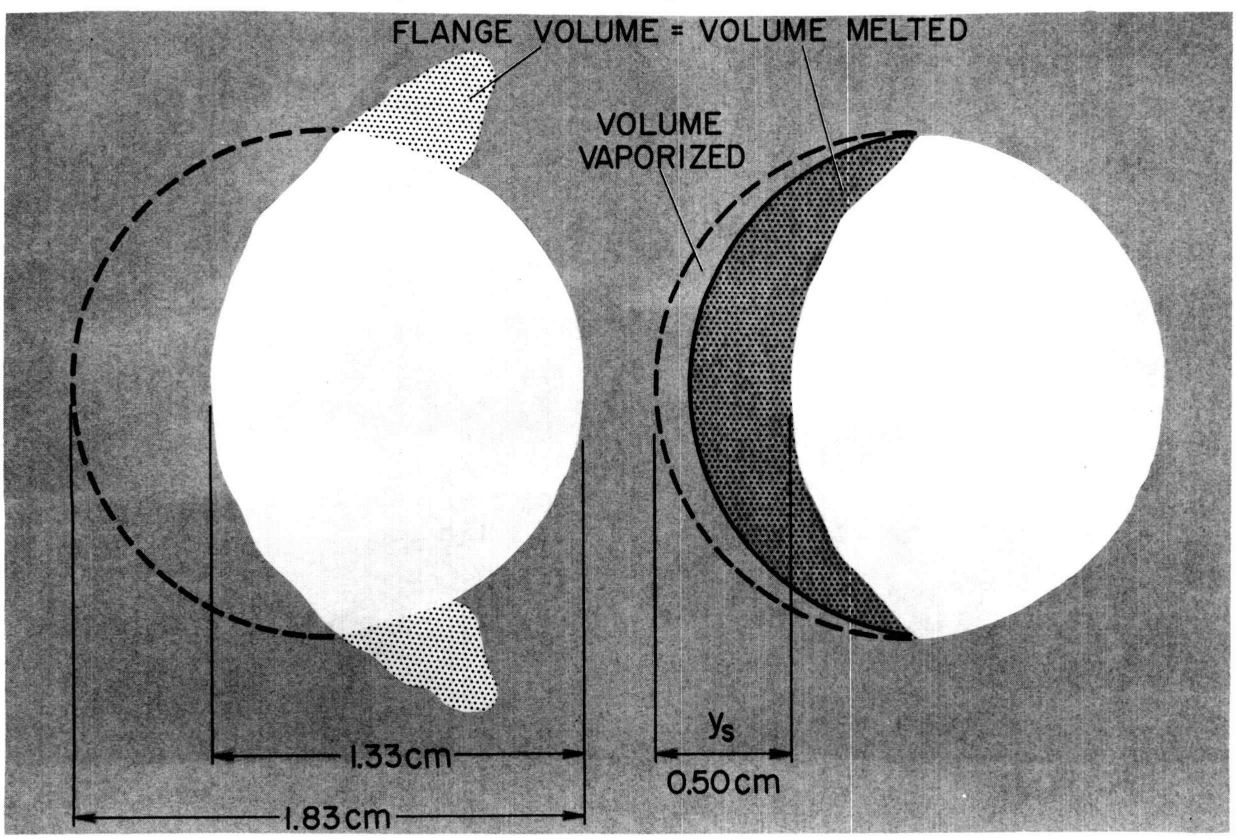


Figure 9.- Reconstruction of australite C625.

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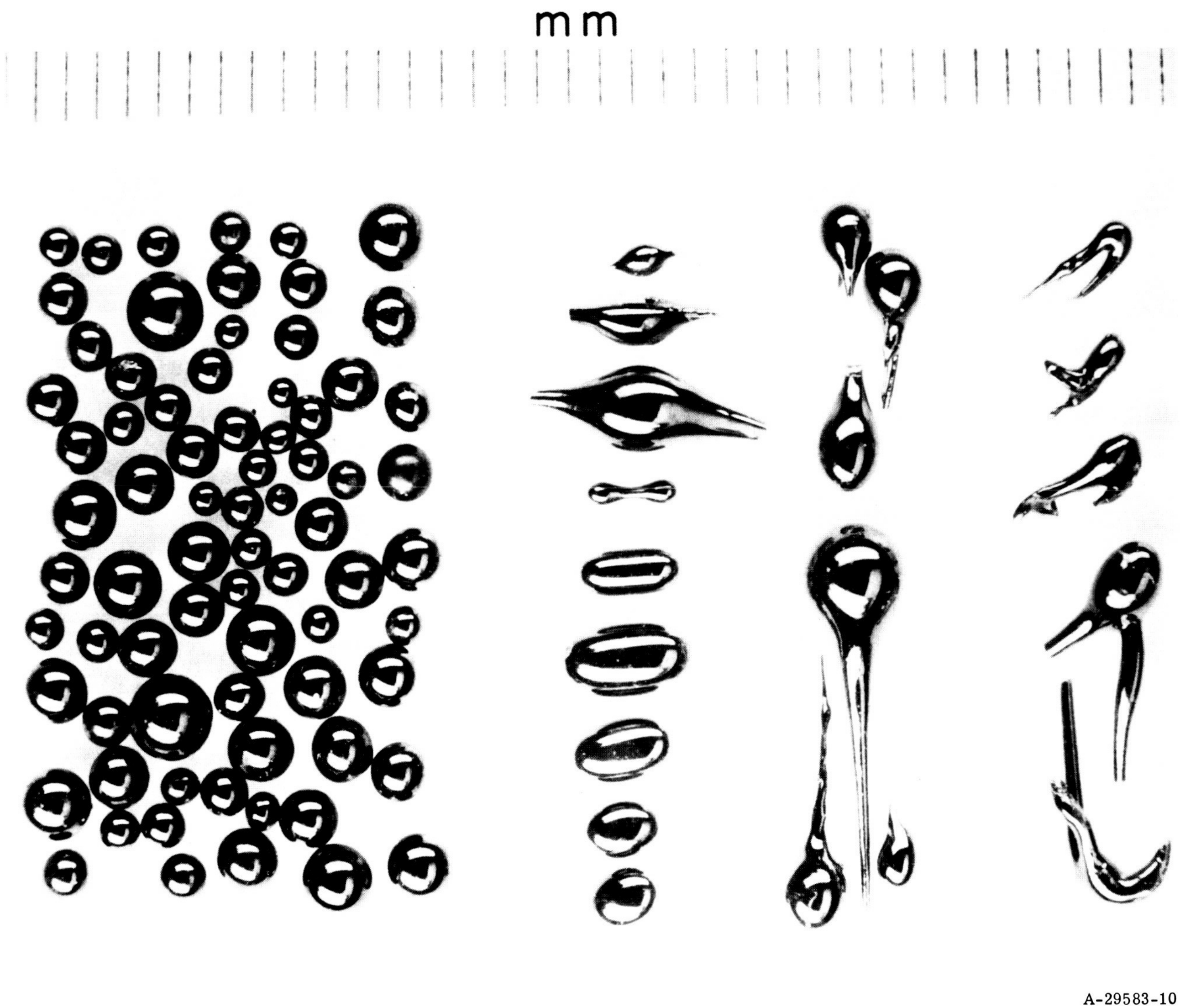

Figure 10.- Forms produced by break-up of glass jet under conditions of negligible aerodynamic forces.

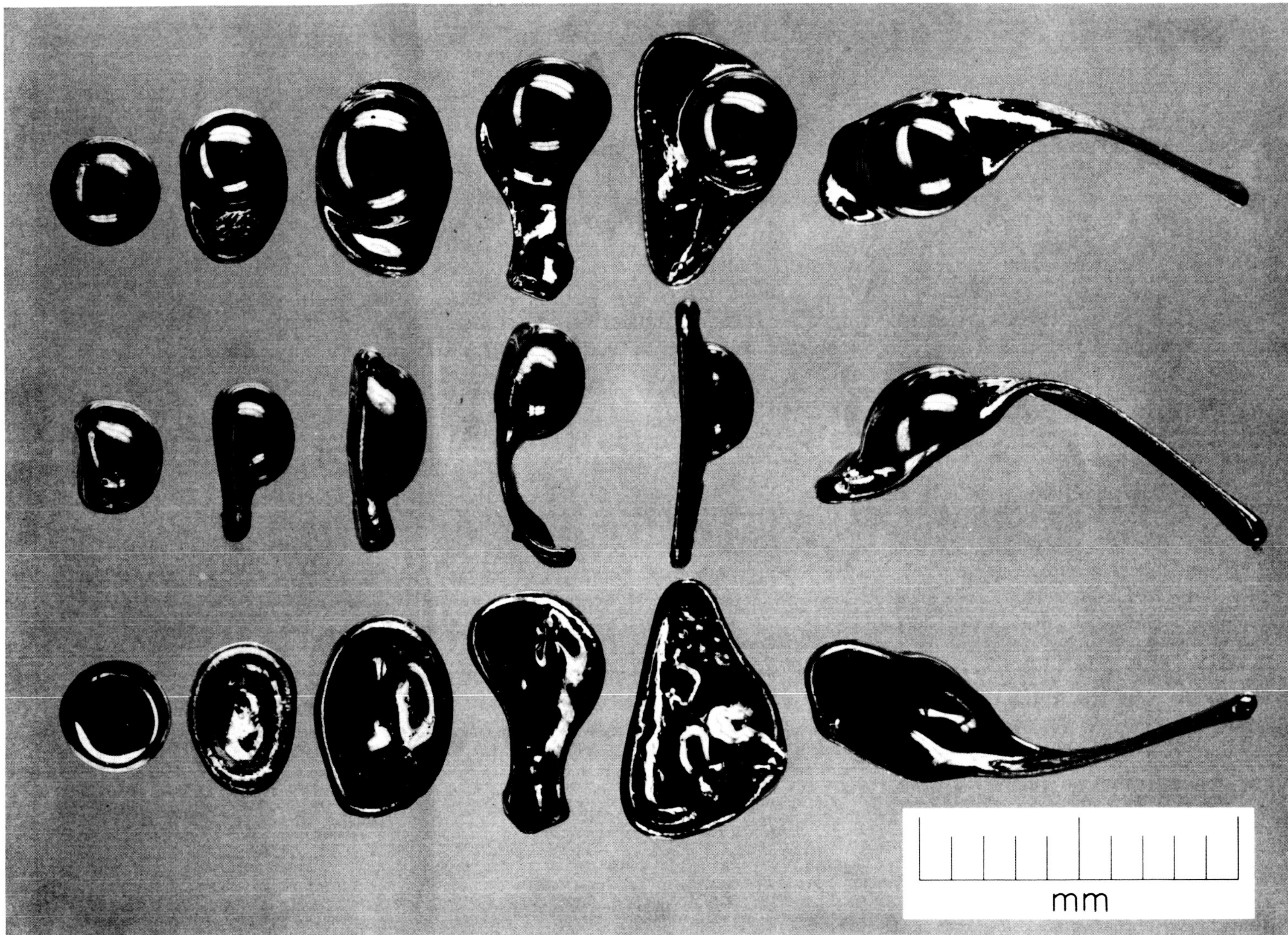

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Figure 11.- Glass drops distorted by aerodynamic pressures.

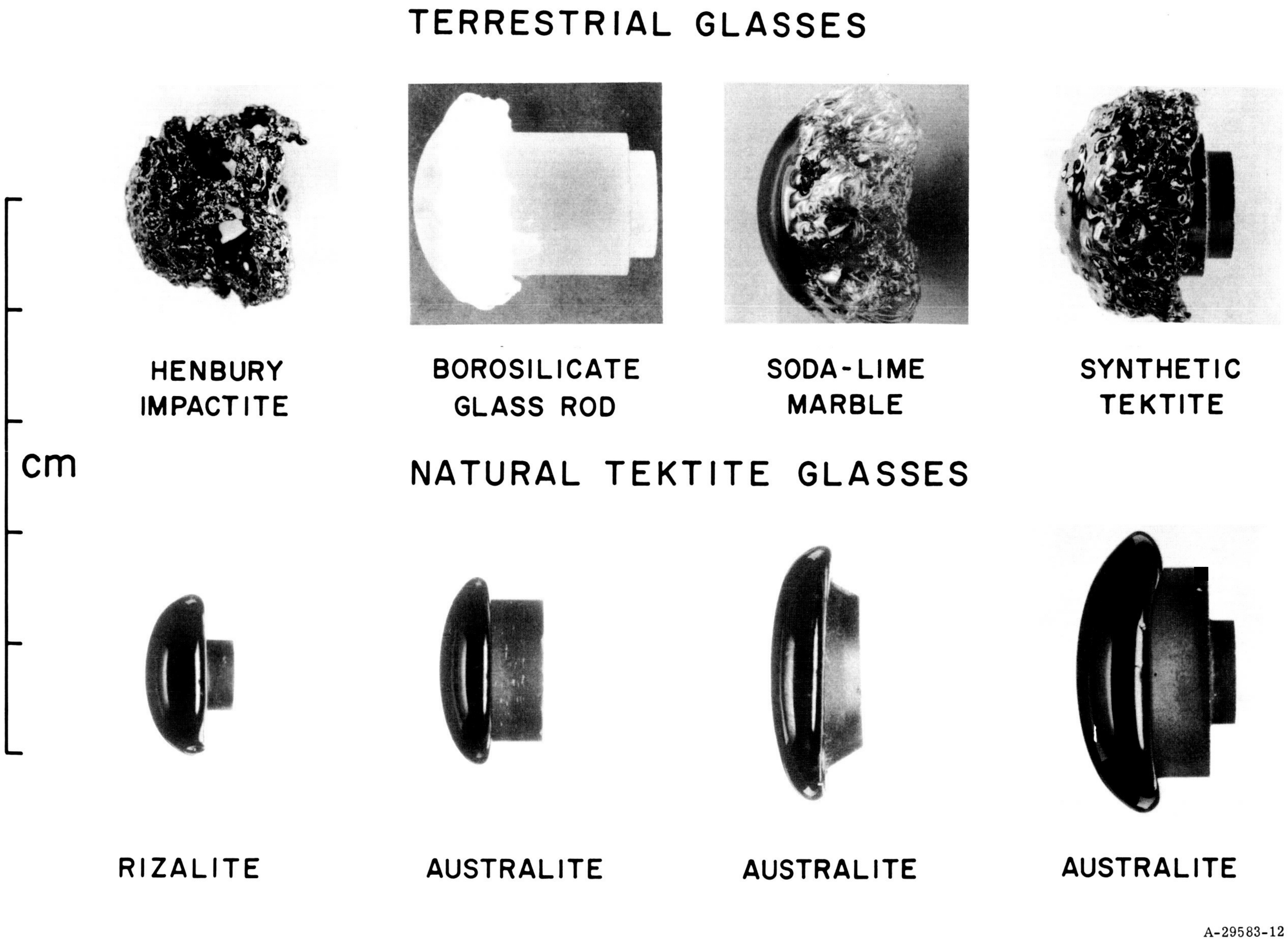


Figure 12.- Models after ablation at low pressure.

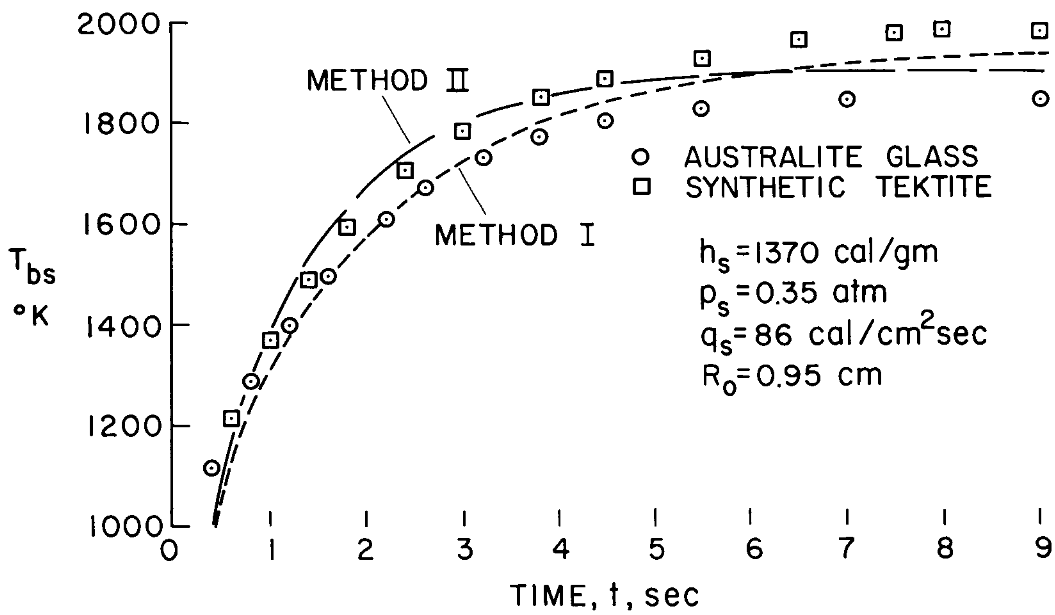


Figure 13.- Comparison of calculated and measured brightness temperature during aerodynamic ablation.

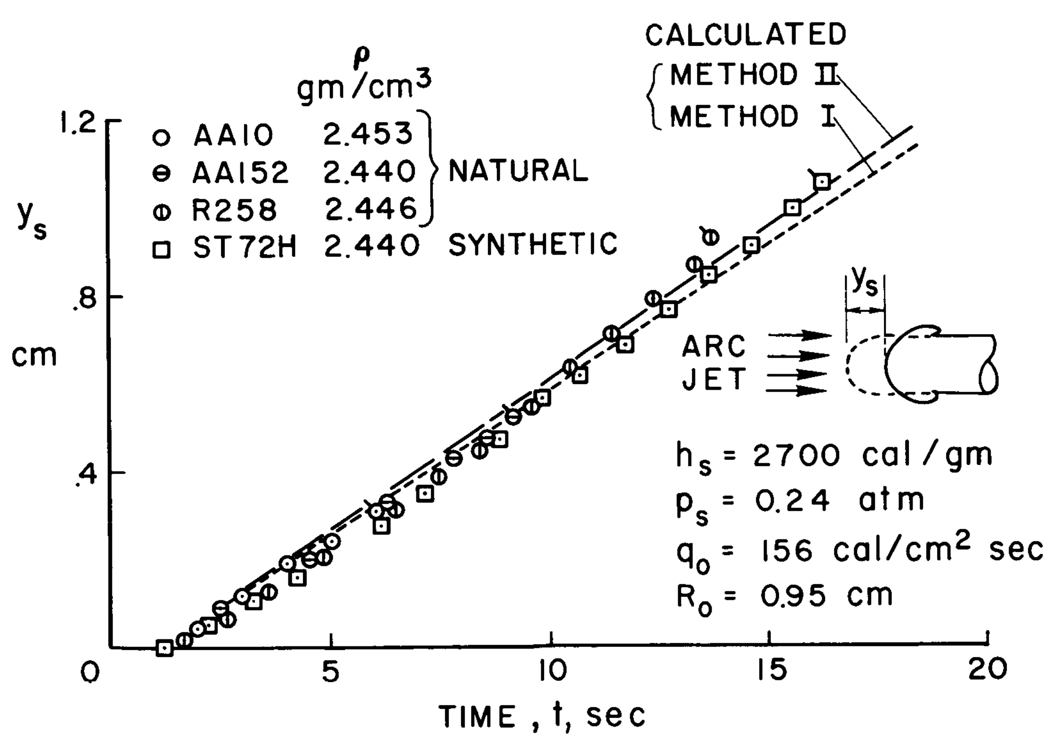


Figure 14.- Calculated and measured ablation rates for natural and synthetic tektite glass.

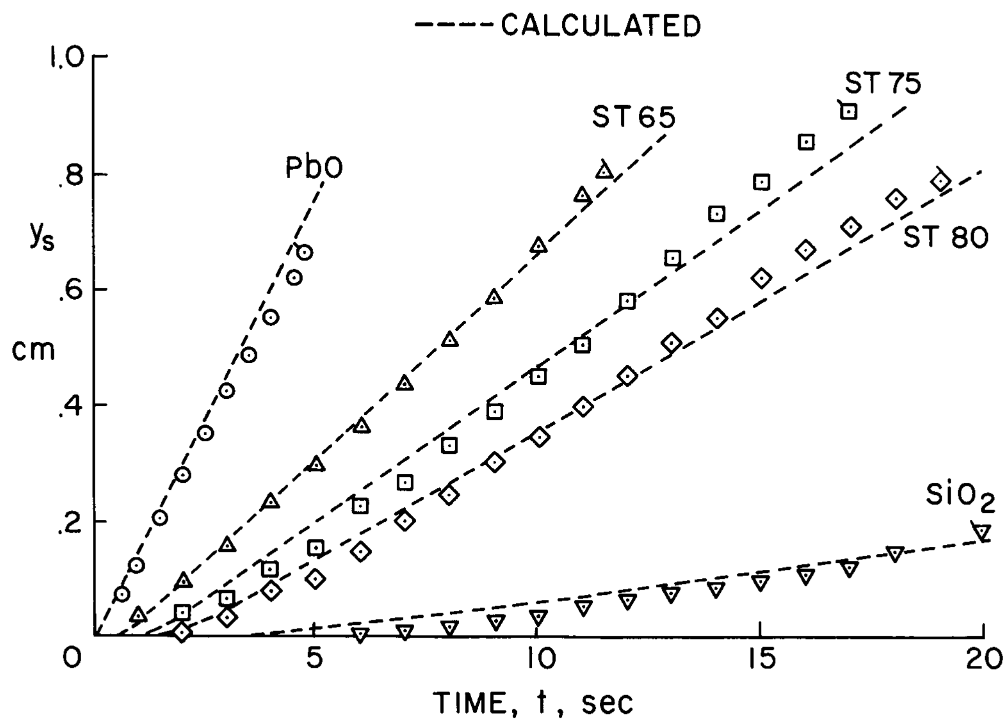


Figure 15.- Calculated and measured ablation rates for various glasses.

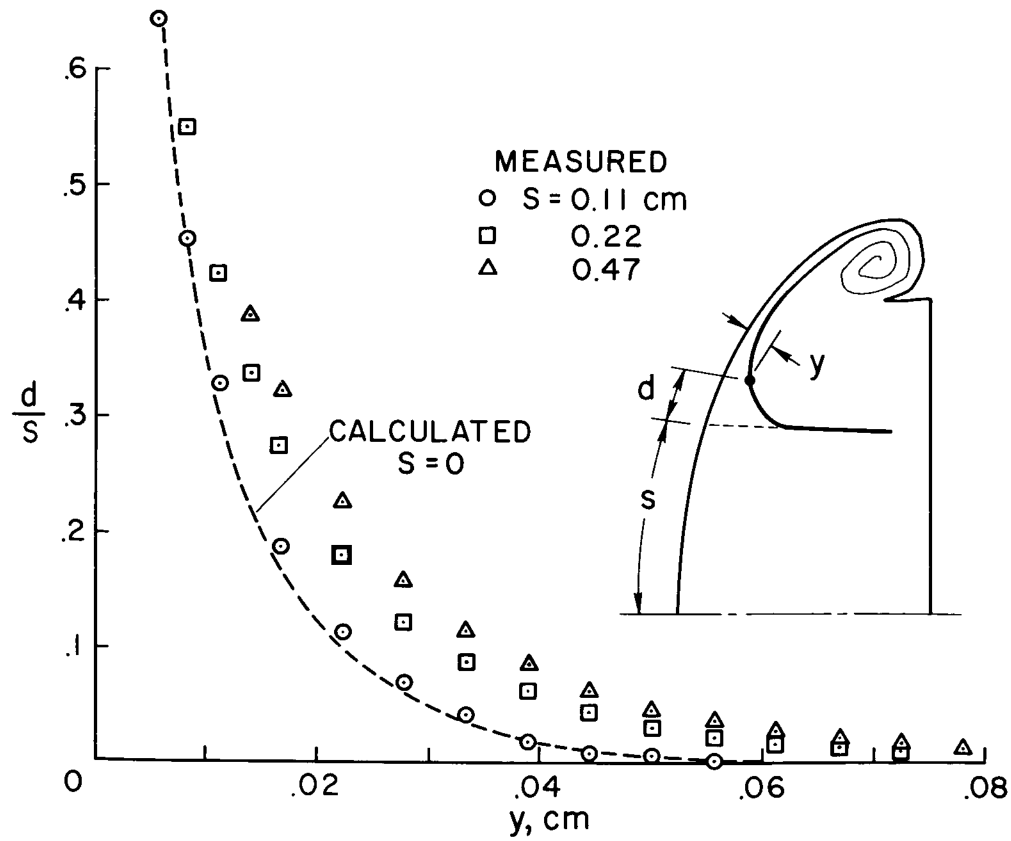
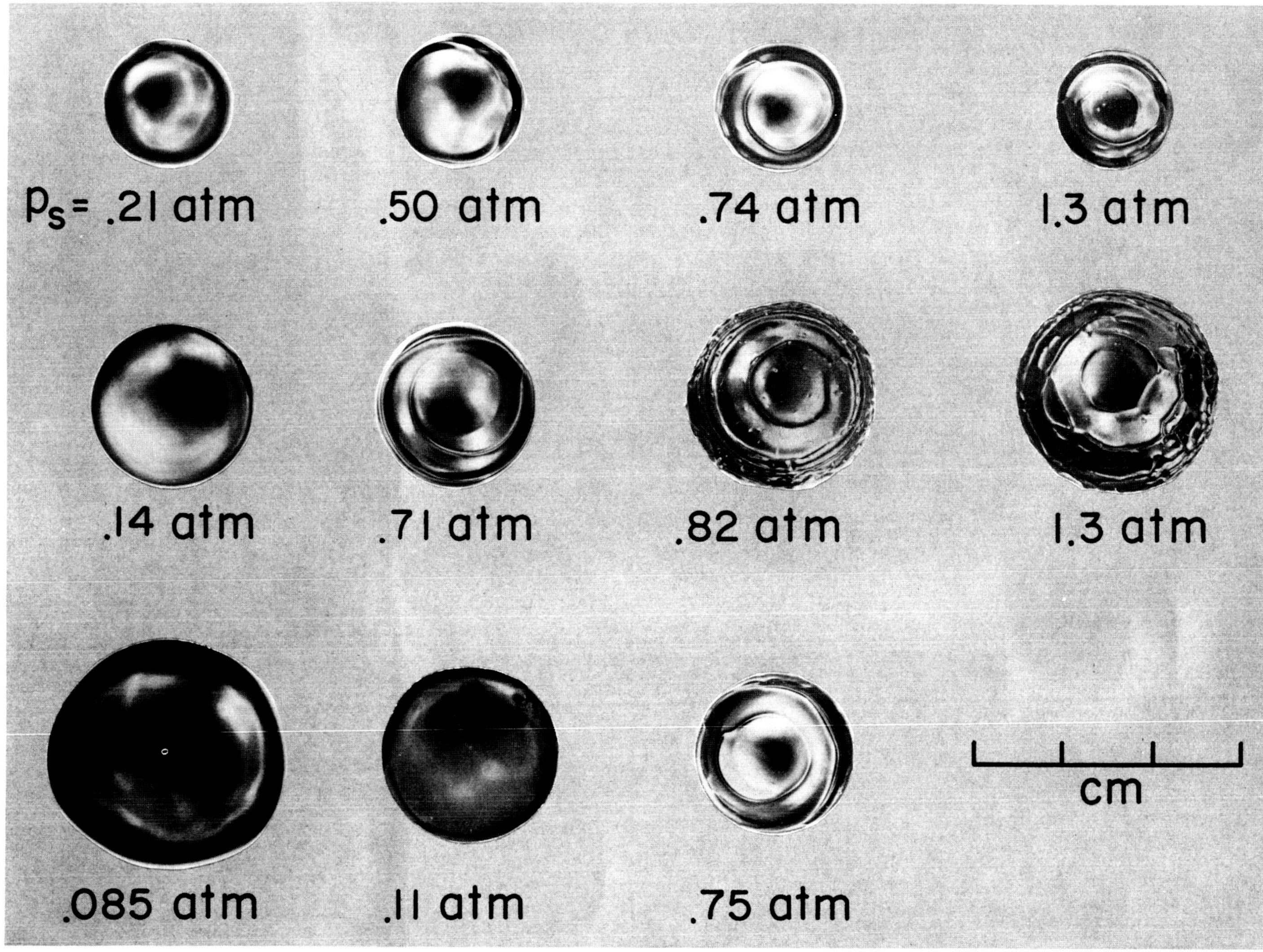


Figure 16.- Calculated and measured striae displacement.



A-29583-17

Figure 17.- Dependence of ring-wave flow ridges on stagnation pressure.

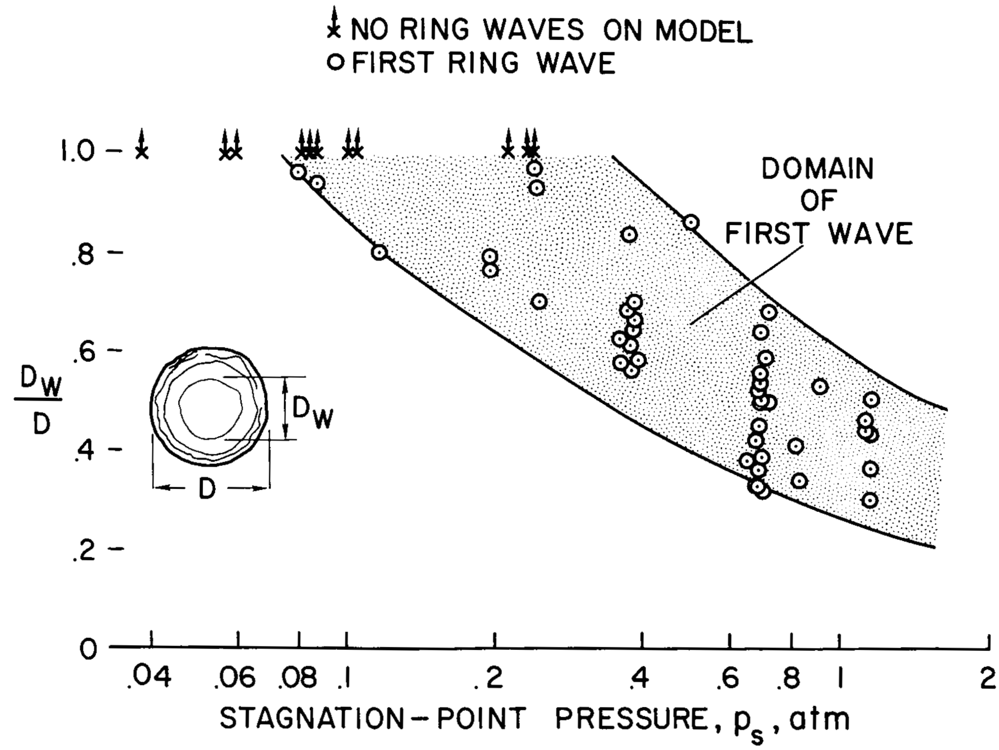


Figure 18.- Dependence of ring-wave diameter on pressure.

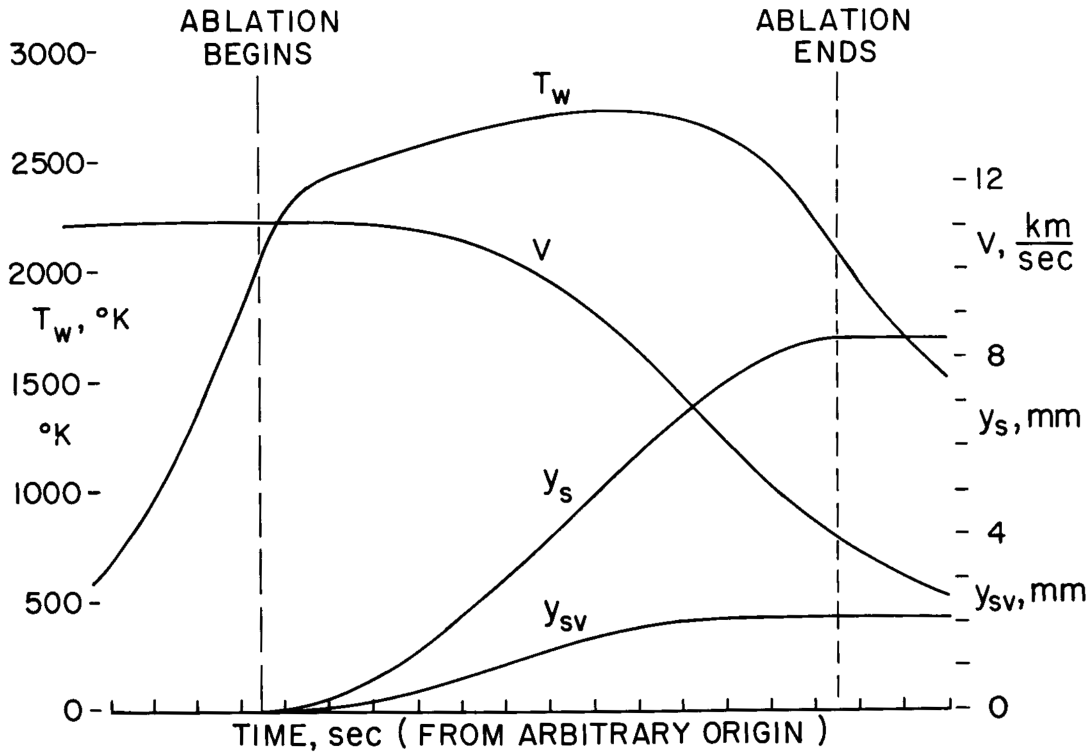


Figure 19.- Variation of temperature, velocity, total ablation, and vaporized ablation during entry of australite into the earth's atmosphere; V_i = 11.2 km/sec, γ_i = 20°.

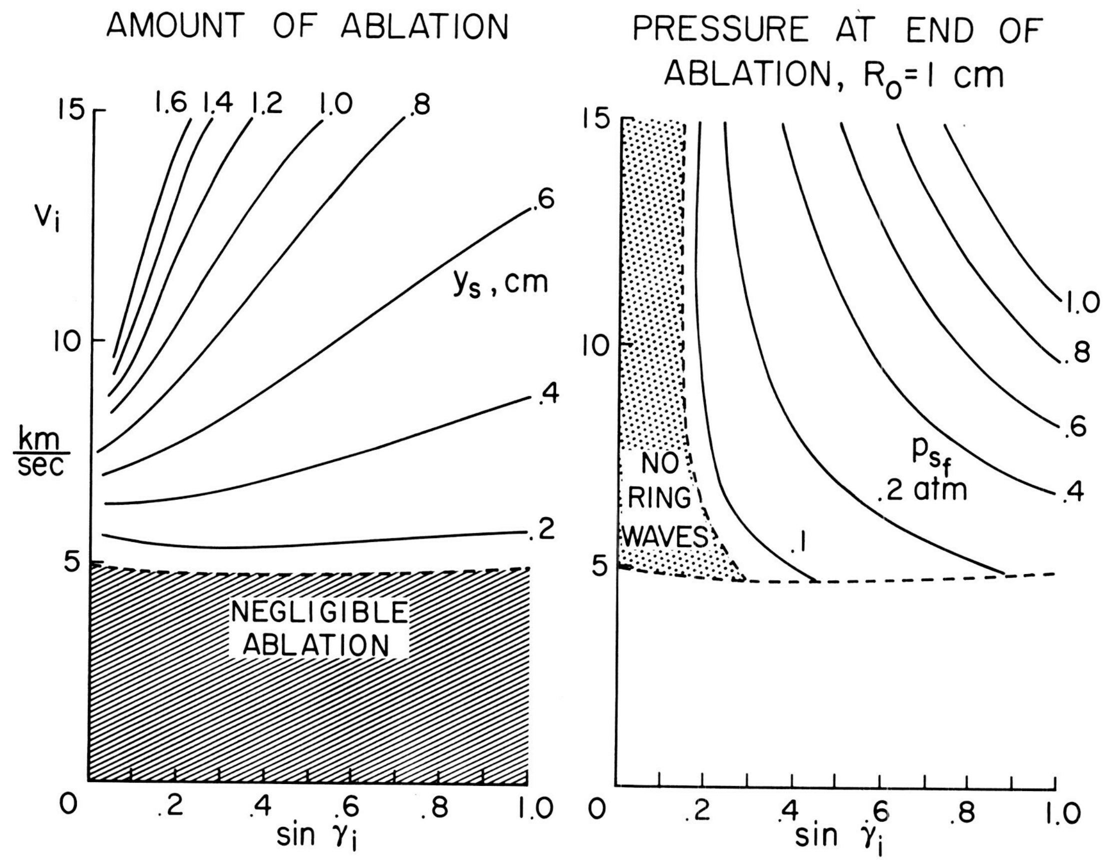


Figure 20.- Lines of constant amount of ablation, and constant stagnation pressure prior to termination of ablation, for entry of australite sphere of 1-cm radius into earth's atmosphere.

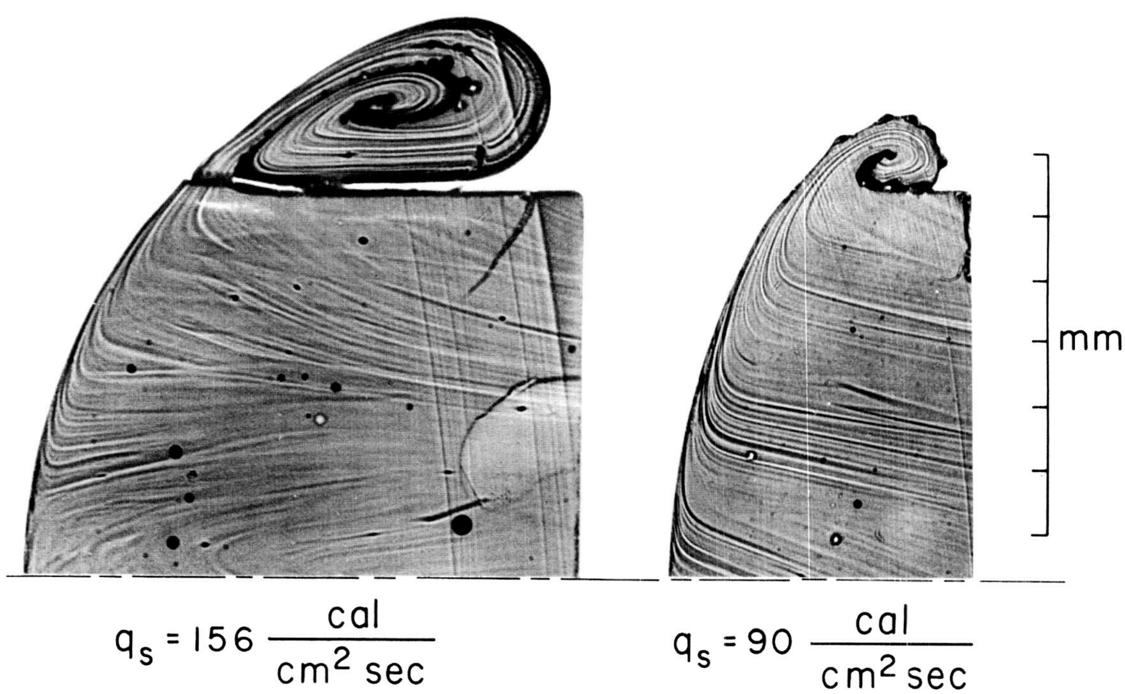
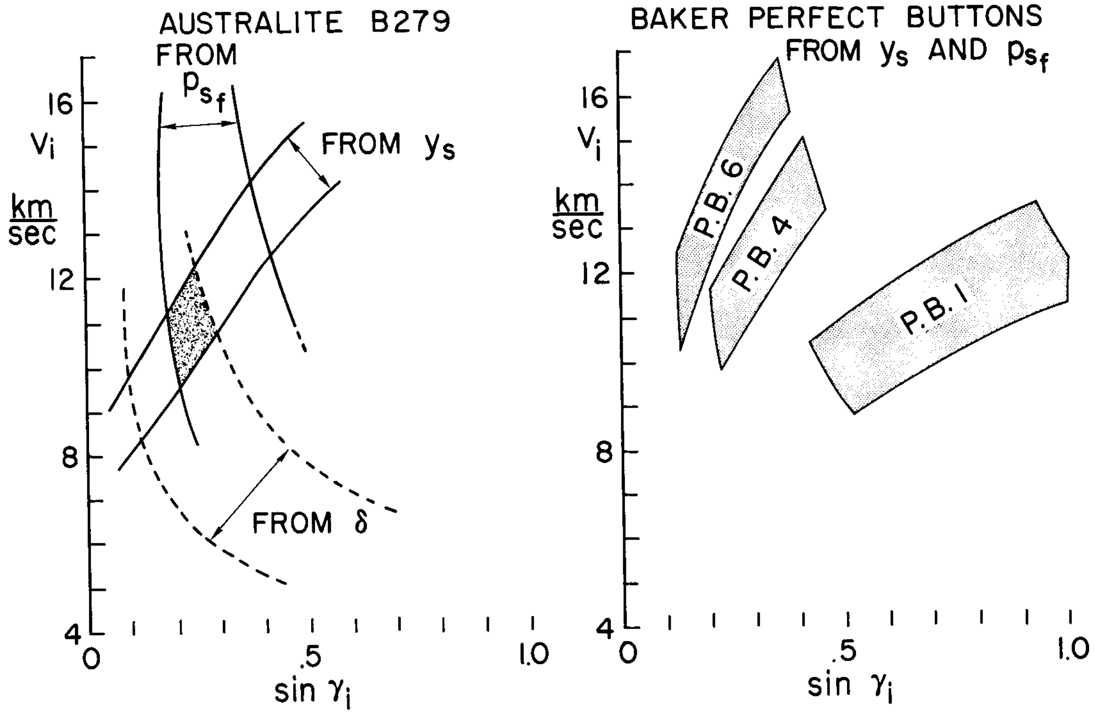
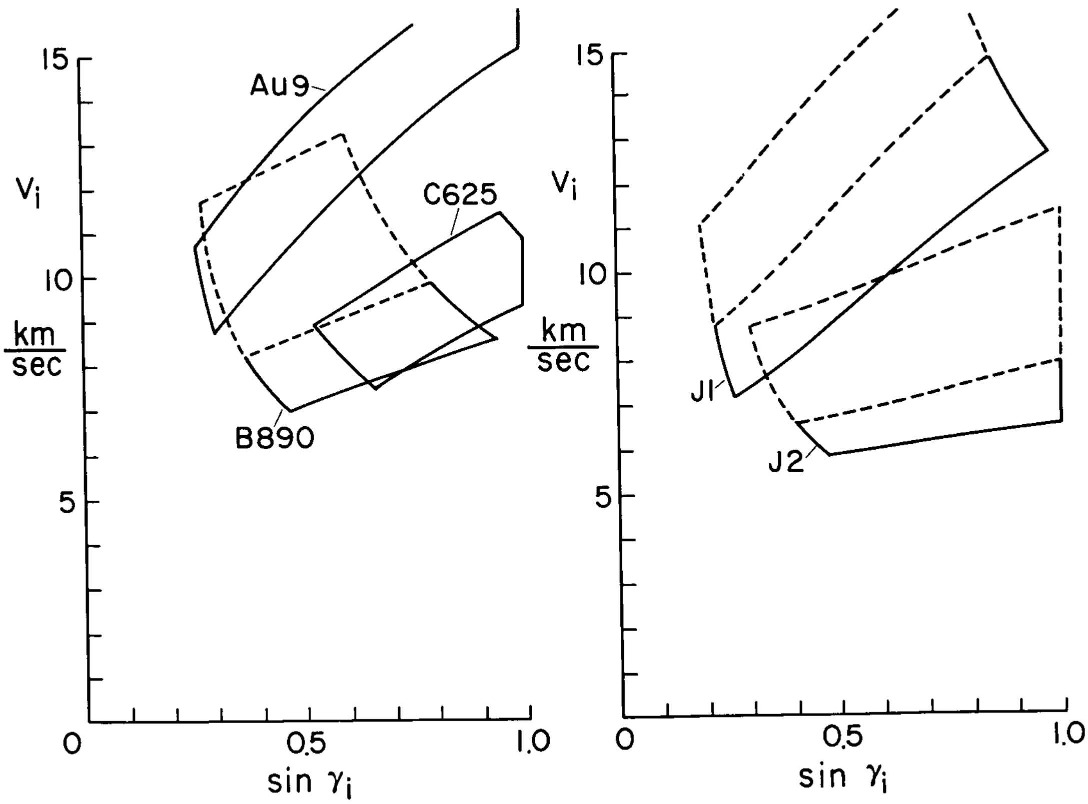


Figure 21.- Illustration of inverse variation of liquid layer thickness with heating rate.



(a) Australites from Port Campbell, Victoria.



(b) Other australites and javanites.

Figure 22.- Domains for atmosphere entry of tektites.

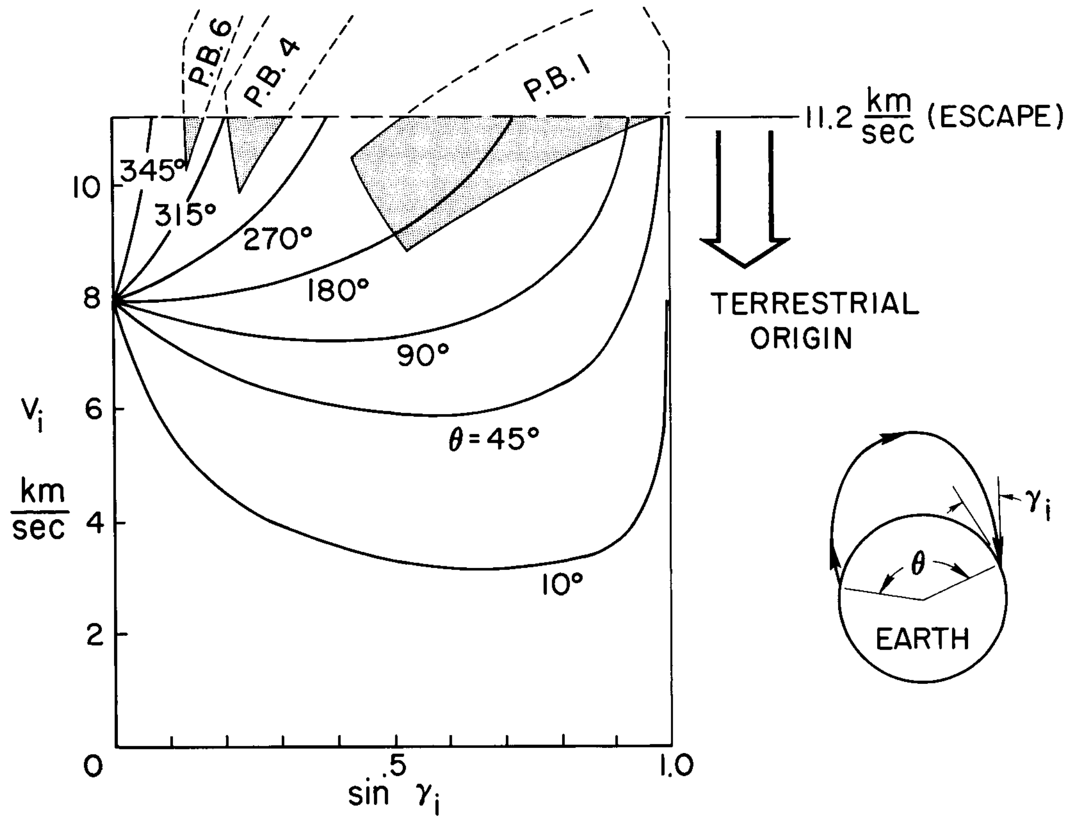


Figure 23.- Test of terrestrial origin hypothesis.

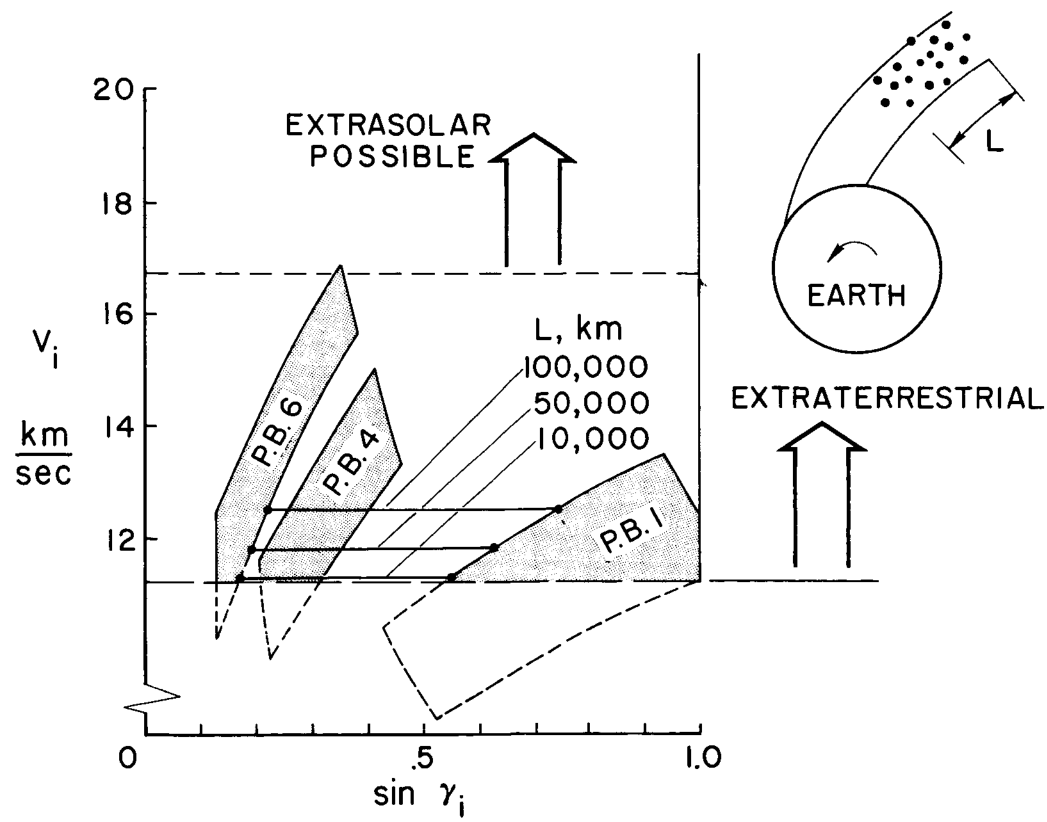


Figure 24.- Test of hypothesis of extraterrestrial origin.

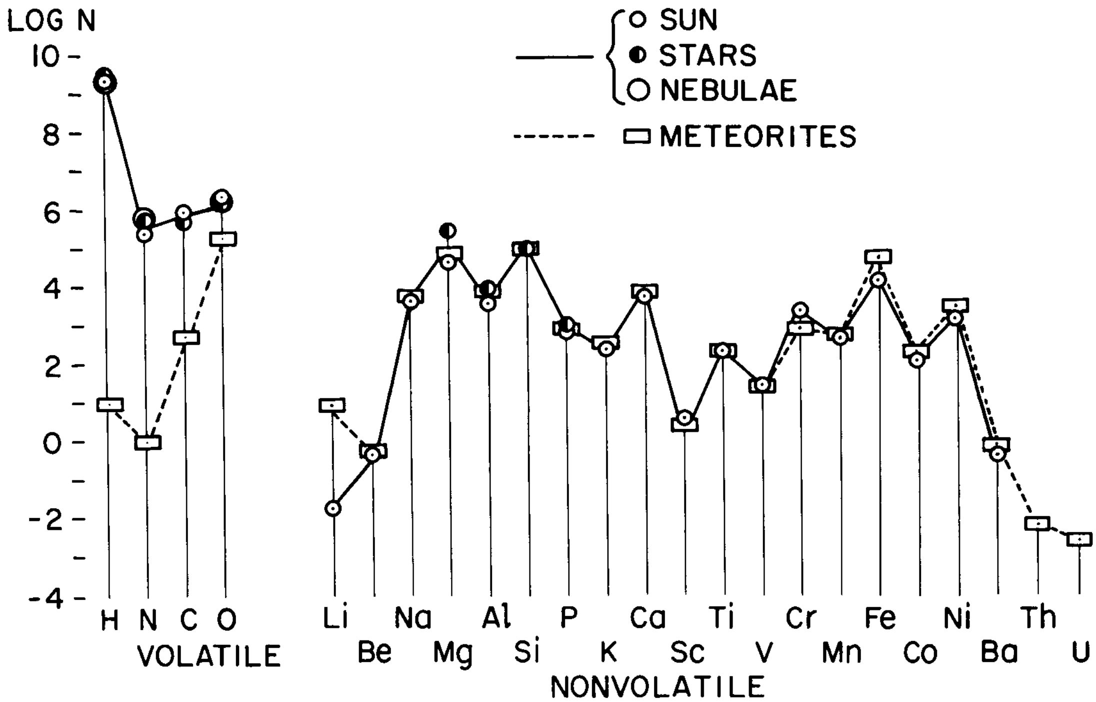


Figure 25.- Abundance of elements in stars and meteorites.

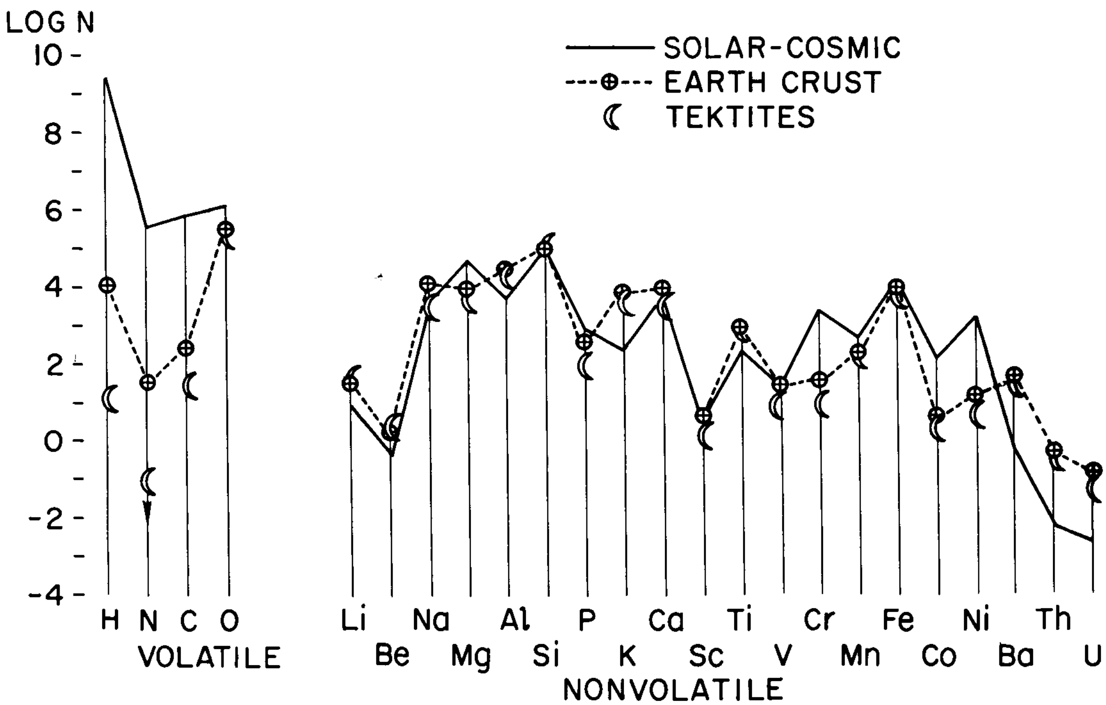


Figure 26.- Abundance of elements in sun, earth crust, and tektites.

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